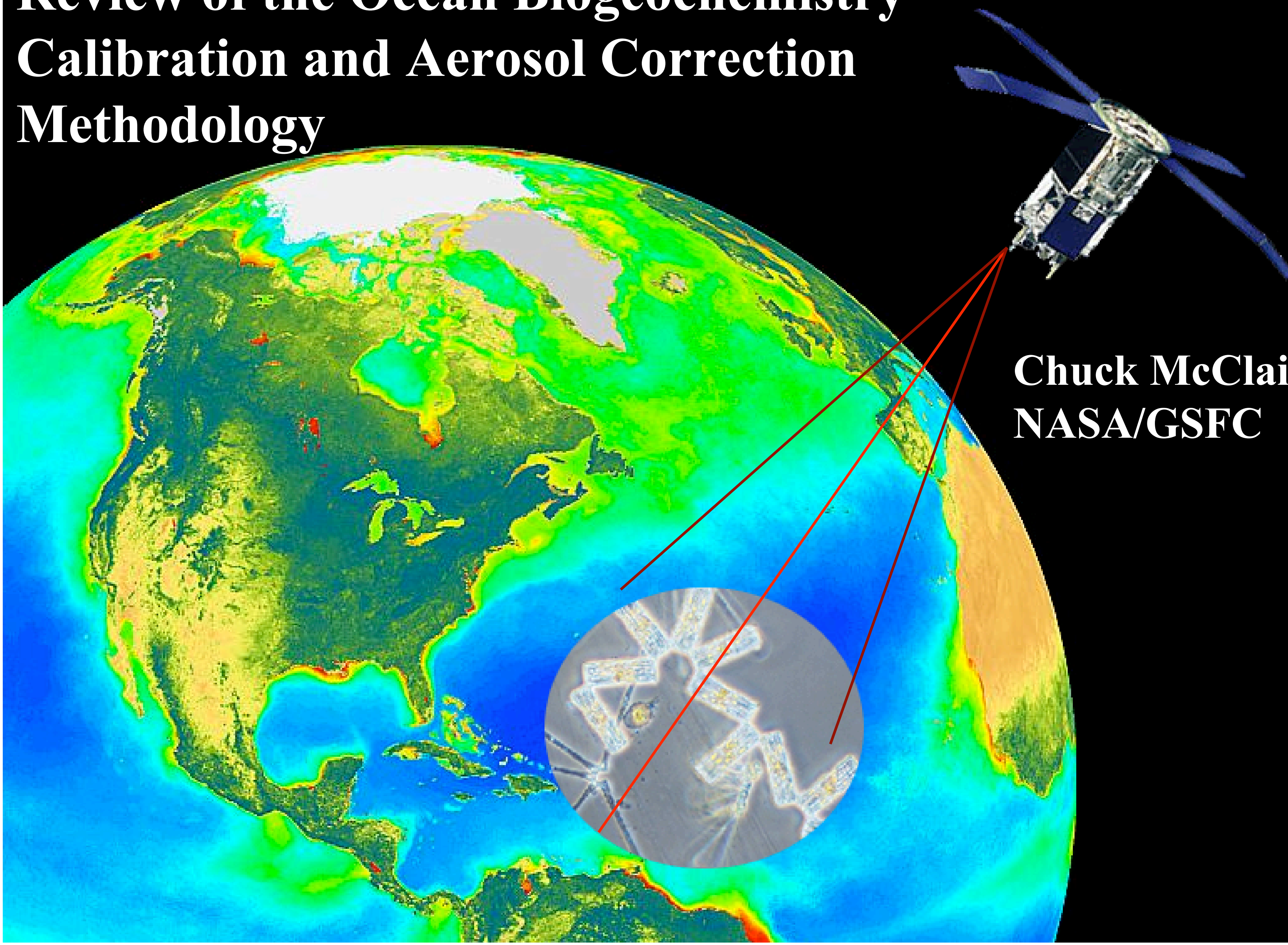
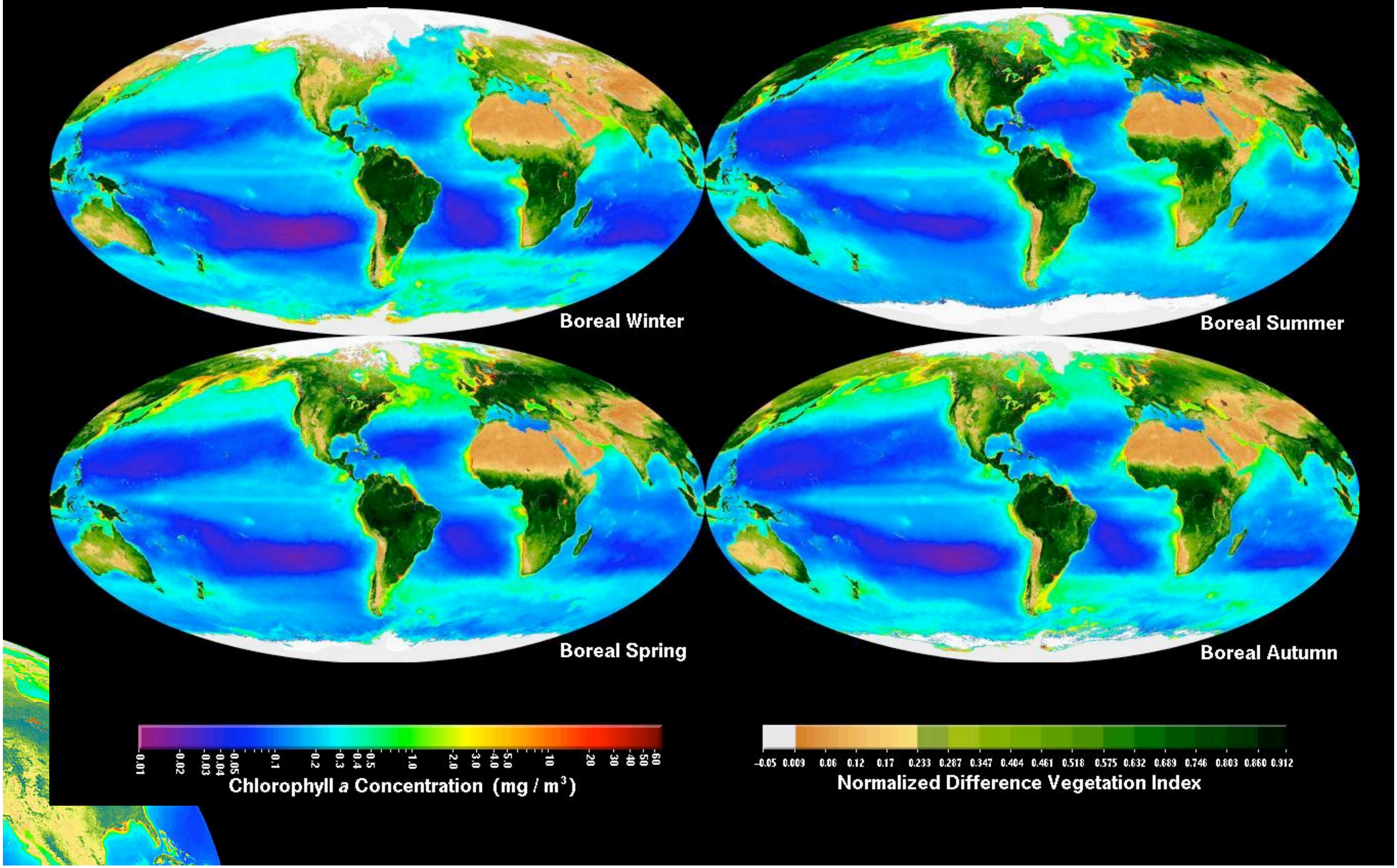
Review of the Ocean Biogeochemistry Calibration and Aerosol Correction Methodology



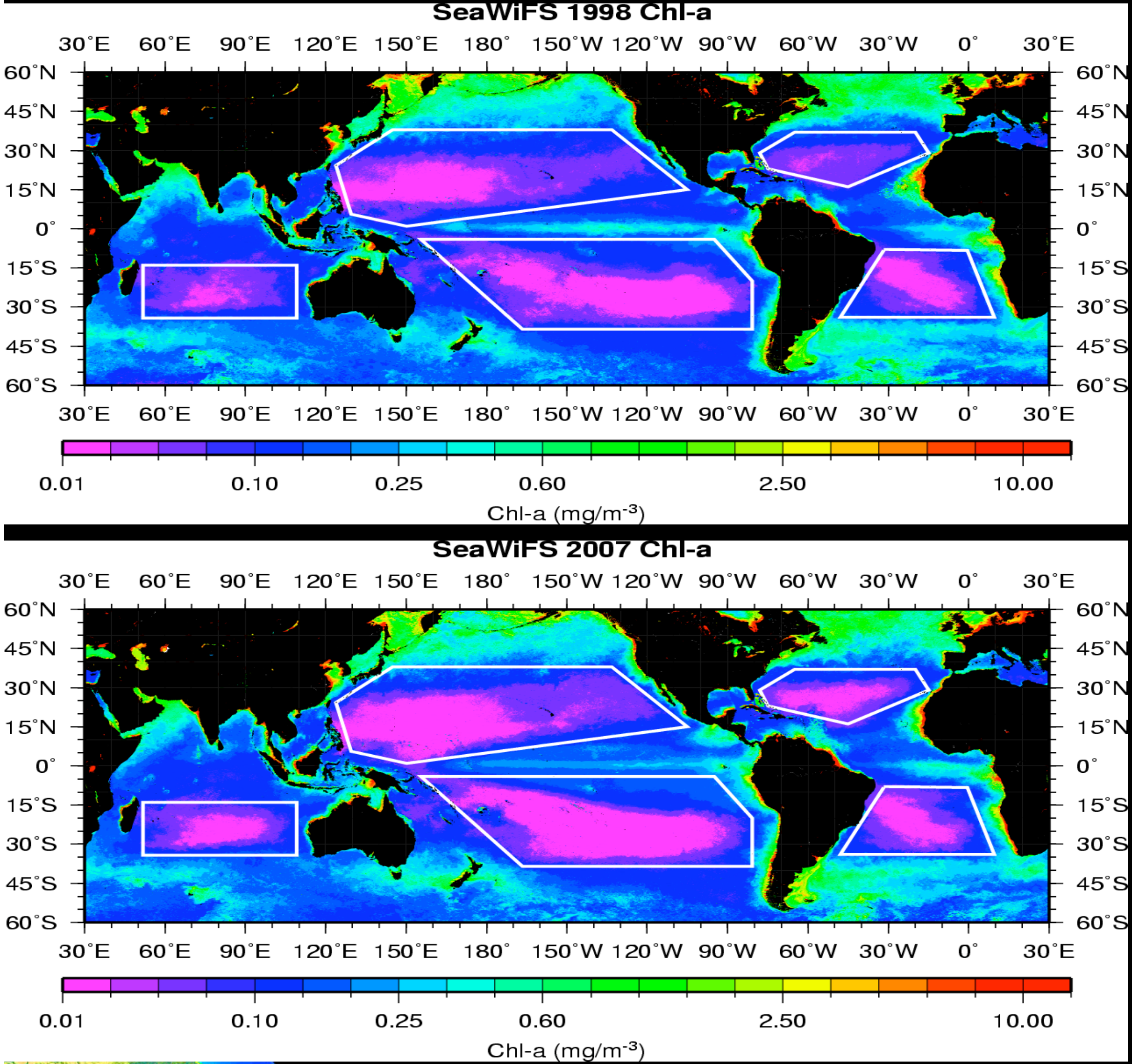
Chuck McClain
NASA/GSFC

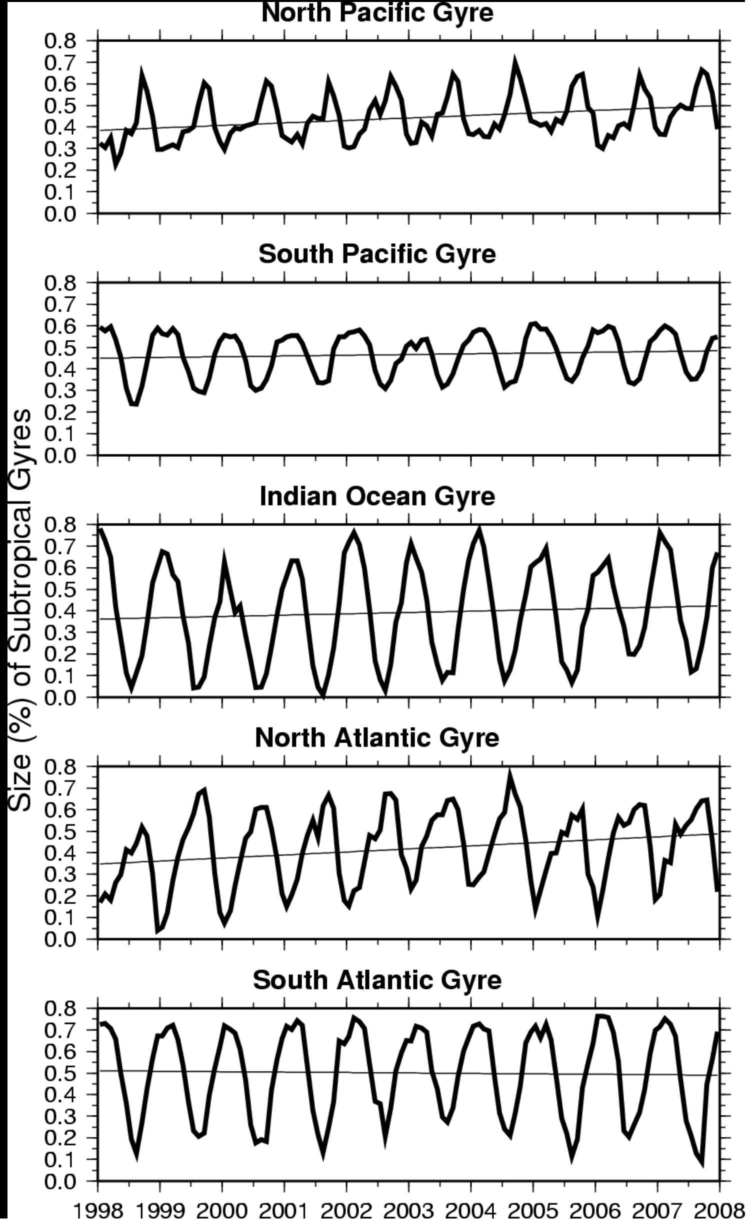
Seasonal Global Biospheres

SeaWiFS Climatologies (1997-2002)



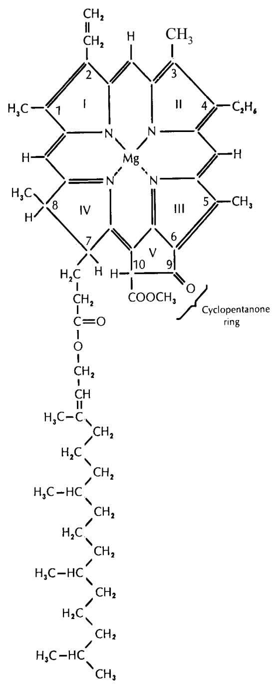
Decadal Scale Biological Variability

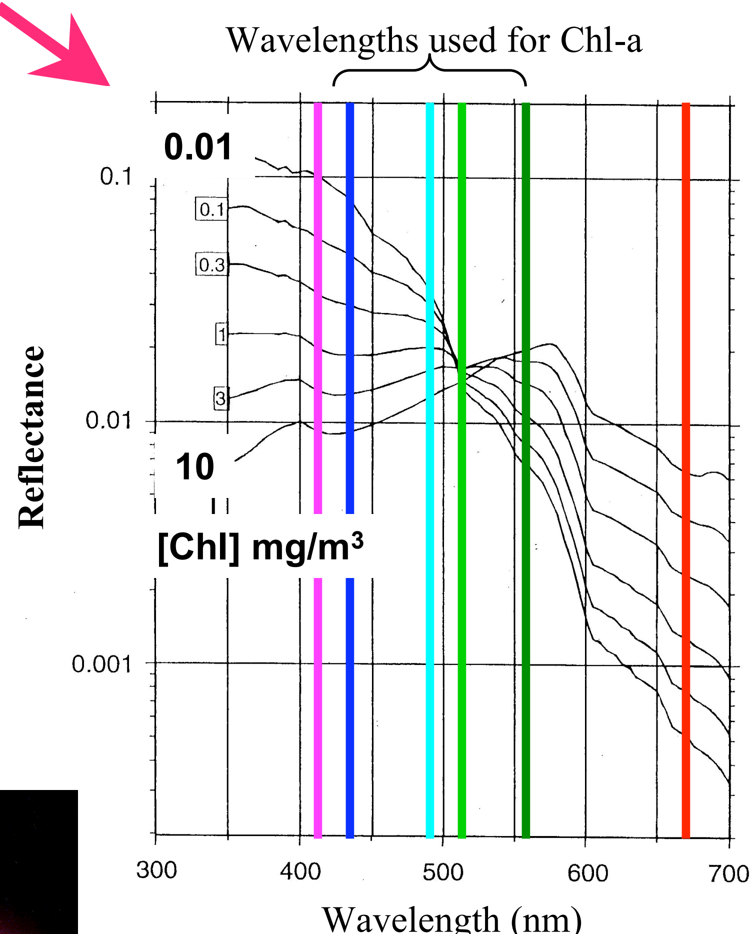




Quantifying Phytoplankton from Space: Chl-a Algorithm

Chlorophyll-a

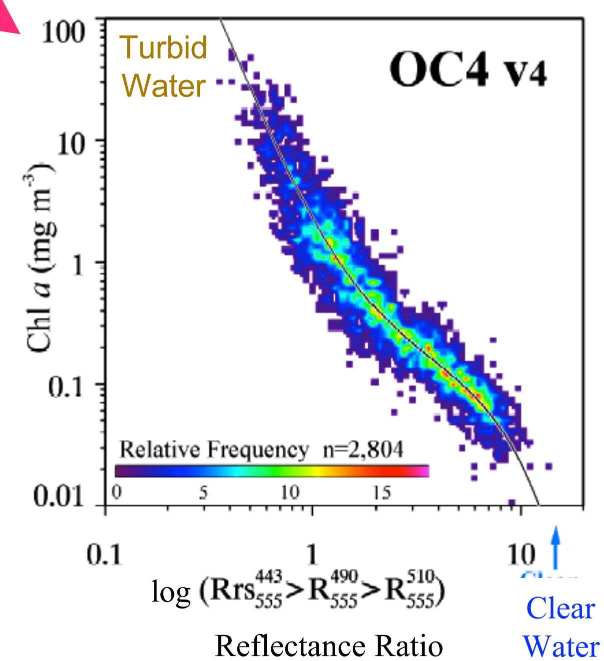




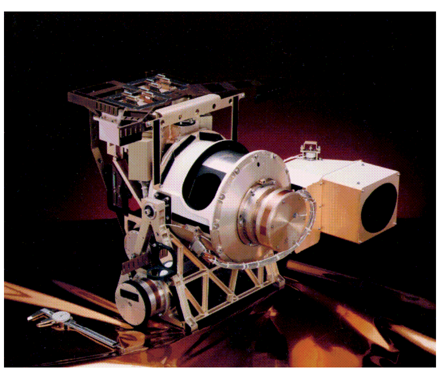
Marine Spectral Reflectance vs. Chlorophyll-a

From chlorophyll absorption to chlorophyll concentration via optics

Chlorophyll Algorithm: Statistical "Band-Ratio" Regression



SeaWiFS



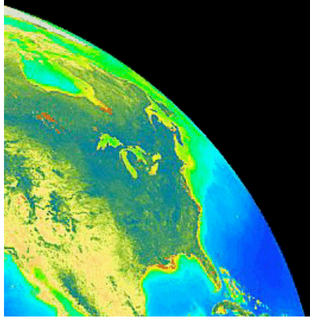
NASA Ocean Color Accuracy Goals

- **Sensor radiometric calibration**

  ±0.5% absolute
- **Water-leaving radiances**

  ±5% absolute
- **Chlorophyll-a**

  ±35% over range of 0.05-50.0 mg/m^3



Note: NPOESS Climate Data Record accuracy goals are different.

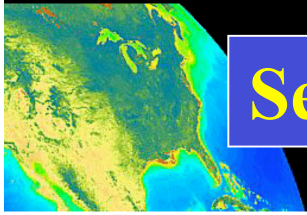
SeaWiFS, MODIS, & VIIRS

- **SeaWiFS**
  - Rotating telescope
  - 412, 443, 490, 510, 555, 670, 765, 865 nm bands
  - 12 bit digitization truncated to 10 bits on spacecraft
  - 4 focal planes, 4 detectors/band, 4 gain settings, bilinear gain configuration
  - Polarization scrambler: sensitivity at 0.25% level
  - Solar diffuser (daily observations)
  - Monthly lunar views at 7° phase angle via pitch maneuvers

- **NPP/VIIRS (Ocean Color)**
  - SeaWiFS-like rotating telescope
  - MODIS-like focal plane arrays (16 detectors/band)
  - 12 bit digitization
  - No polarization scrambler
  - Solar diffuser with stability monitor
  - 7 OC bands (412, 445, 488, 555, 672, 746, 865 nm)
    - Dual gains except 746 nm (single gain)
  - Monthly lunar views at 55° phase angle via space view port with roll maneuvers (feasible, but not approved)

- **MODIS (Ocean Color)**
  - Rotating mirror
  - 413, 443, 488, 531, 547, 667, 678, 748, 870 nm bands
    - Single gain (NIR saturation)
  - 12 bit digitization
  - 4 focal planes (7-11 bands each)
    - OC Visible: 412-547 nm (5 bands-10 detectors each)
    - OC NIR: 667-869 (4 bands-10 detectors each)
  - No polarization scrambler: sensitivity at ~3% level
  - Spectral Radiometric Calibration Assembly (SRCA)
  - Solar diffuser (observations every orbit), Solar Diffuser Stability Monitor (SDSM)
  - Monthly lunar views at 55° phase angle via space view port

"Nominal" common bands

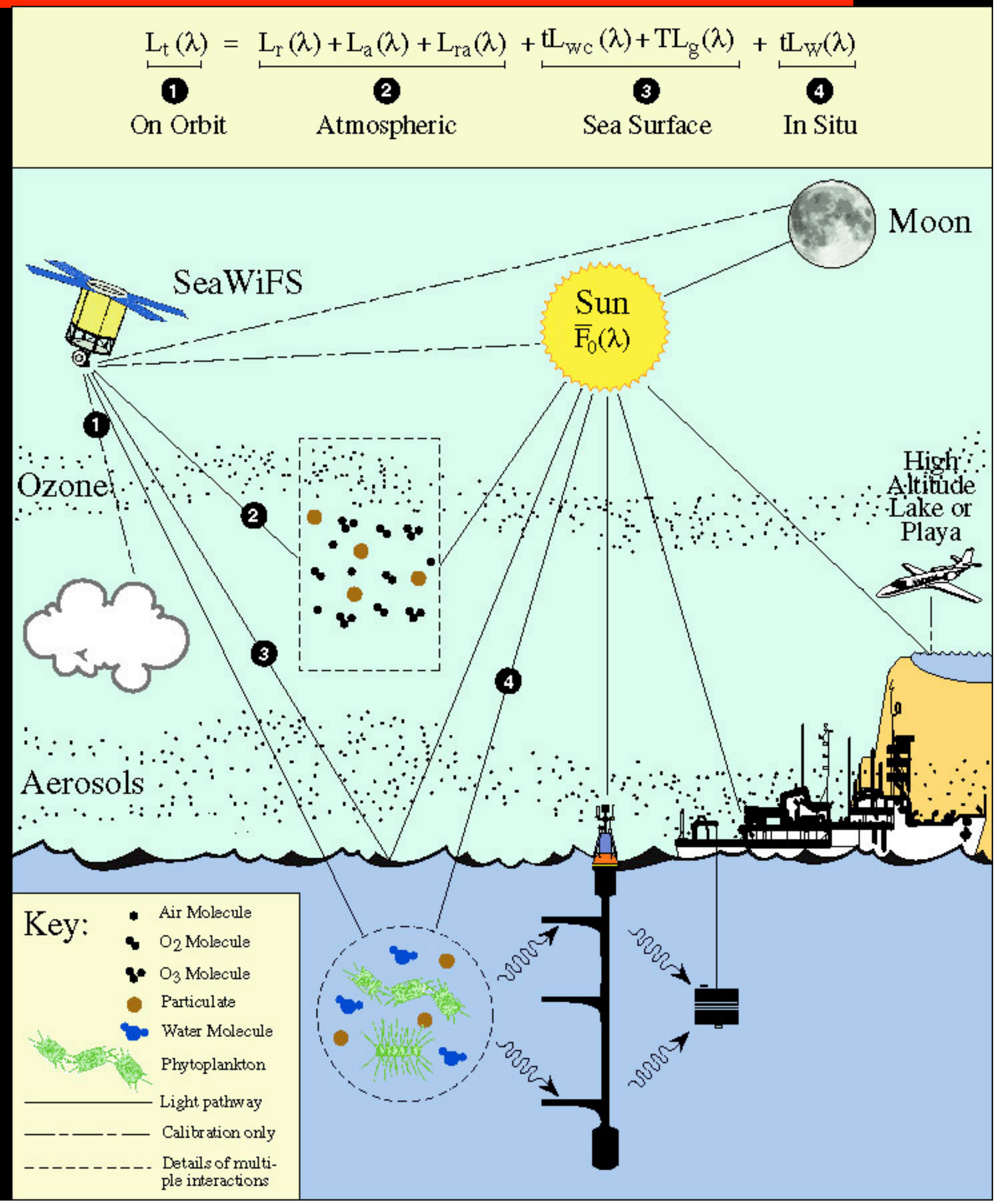


Sensor designs & performance are never identical.

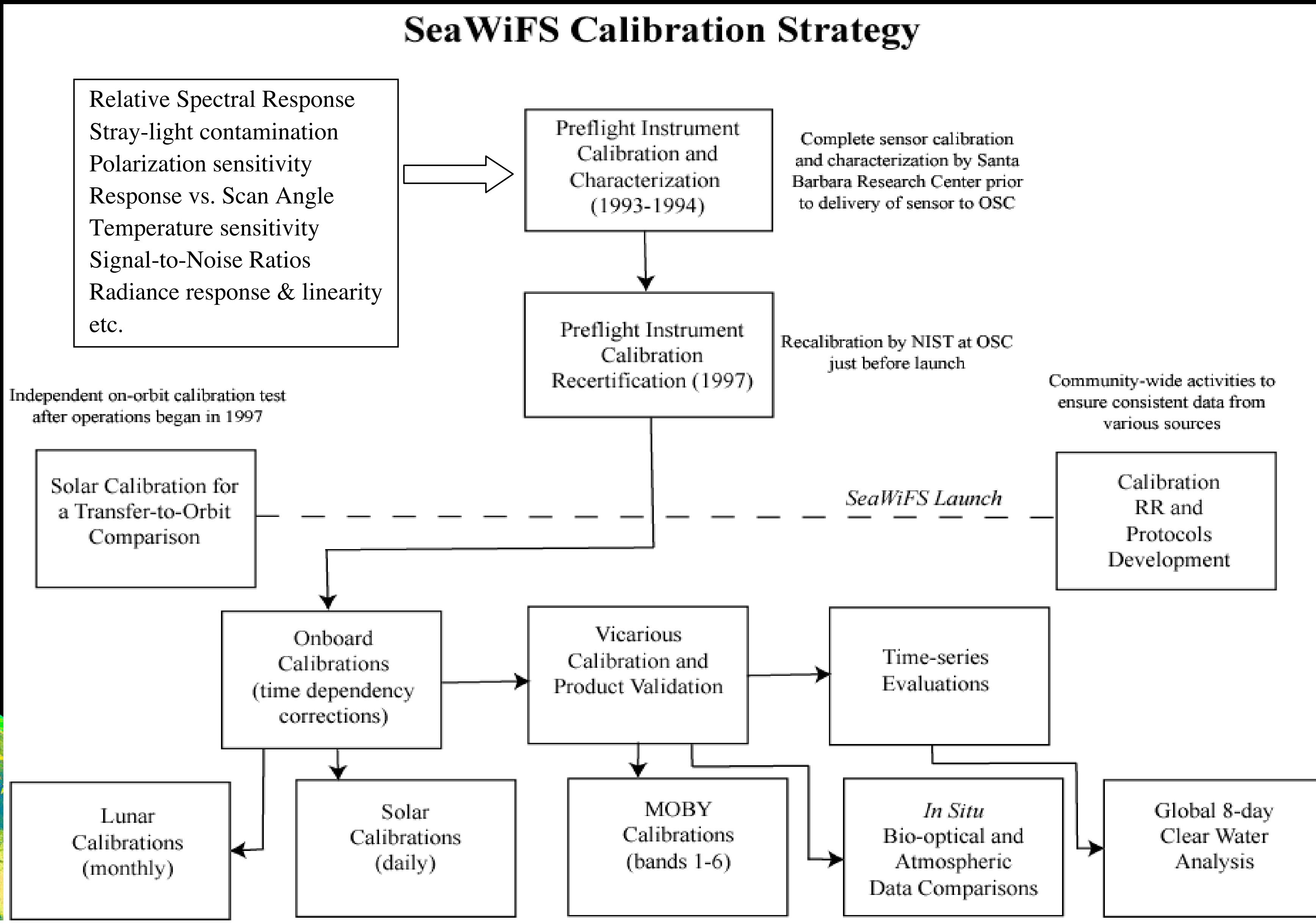
Calibration/Validation Paradigm

Program Elements:

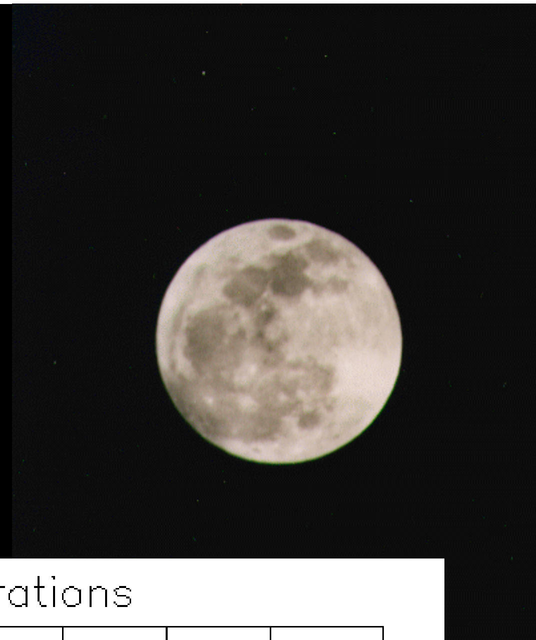
- **Laboratory** - prelaunch sensor calibration & characterization
- **On-orbit** - solar and lunar observations are used to track changes in sensor response
- **Field** - comparison of satellite data retrievals to in-water, above-water and atmospheric observations
  - Vicarious calibration - adjust instrument gains to match water-leaving radiances
  - Product validation (water-leaving radiances, chl-a, etc.)

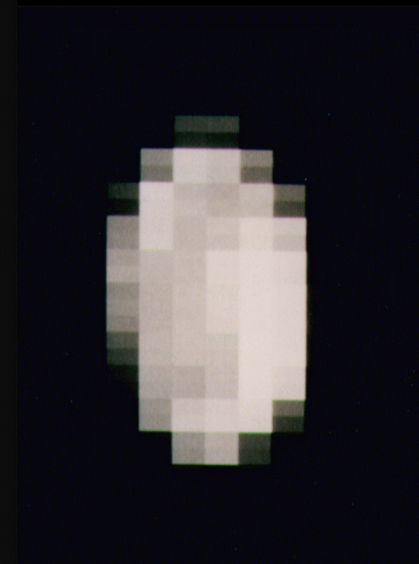


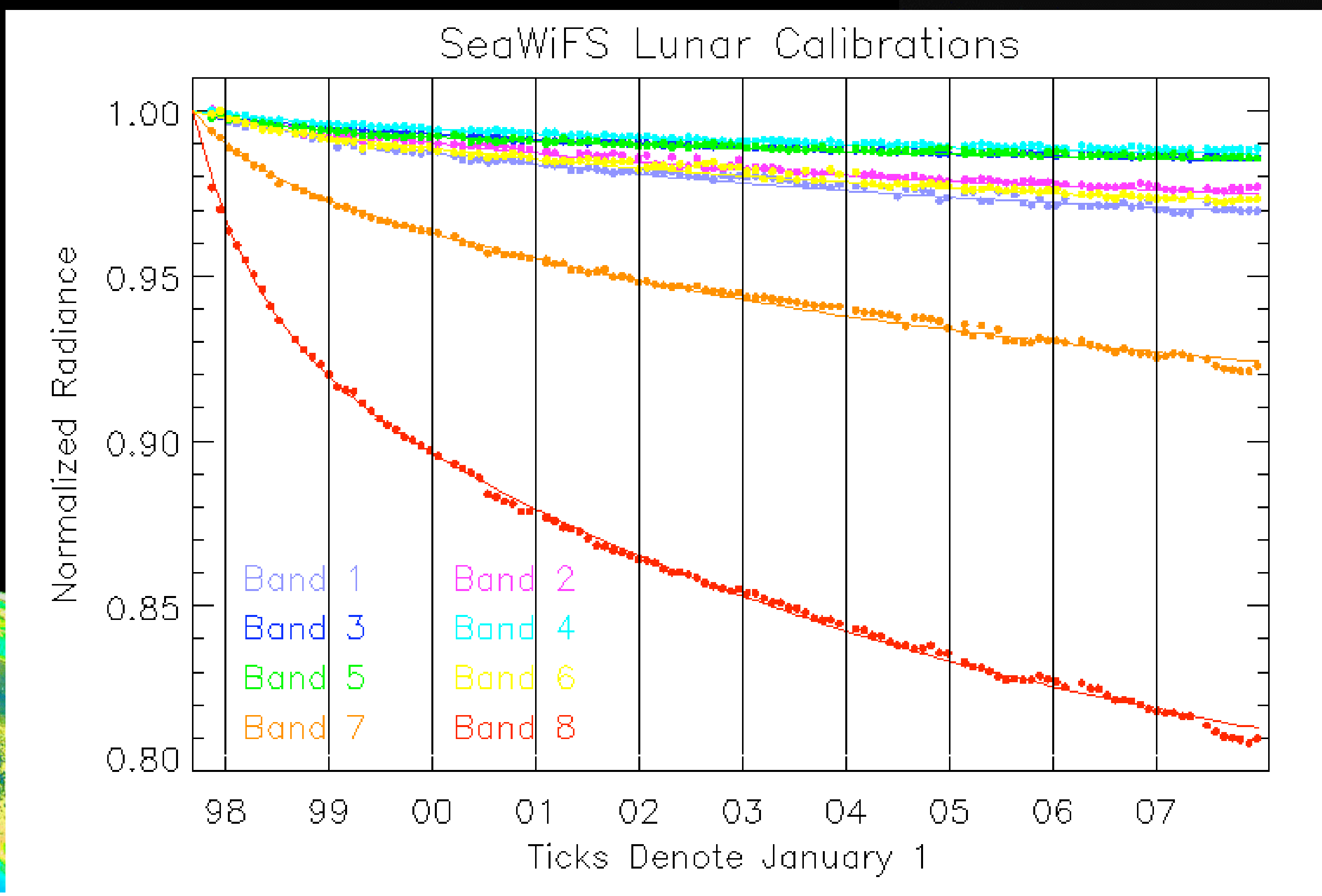
Ocean Color Sensor Calibration Strategy



SeaWiFS Temporal Calibration

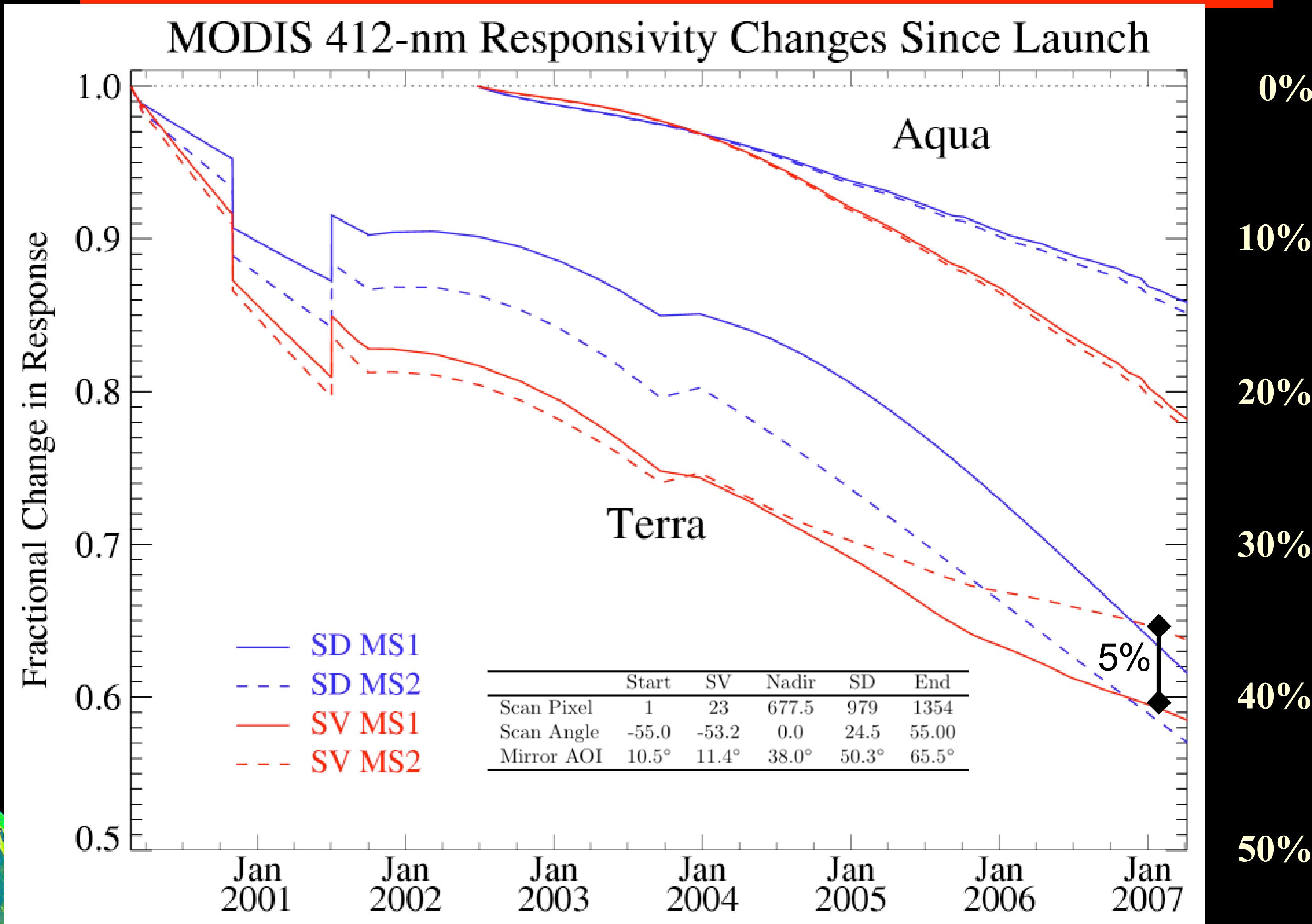






SeaWiFS Band	SeaWiFS λ (nm)
1	412
2	443
3	490
4	510
5	555
6	670
7	765
8	865

MODIS Temporal Degradation at 412 nm
Lunar and Solar Calibration Trends



OC Atmospheric Correction Basics

- Methodology from Gordon & Wang (1994)
  - Assumes NIR reflectance is negligible
  - Models Rayleigh multiple scattering (plane-parallel model)
  - Employs suite of 12 aerosol models (next slide)
  - Uses ratio of NIR aerosol radiances to determine aerosol model
  - Aerosol model extrapolation to visible bands to estimate aerosol radiance
- Glint and white cap radiances modeled using NCEP surface winds
- Gas absorption: Ozone, NO_2 (implemented, not operational), O_2 (SeaWiFS 765 nm only)

OC Atmospheric Correction Basics

$$L_t = [L_r + L_a + T_v L_g + t_{dv} (L_f + L_w)] \; t_{gv} \; t_{gs} \; f_p$$

All terms _-dependent

L_t: measured top of atmosphere radiance

L_r: Rayleigh radiance

L_a: aerosol radiance

T_v: direct transmittance (sensor view)

L_g: glint radiance

t_{dv}: diffuse transmittance (sensor view)

L_f: foam radiance

L_w: water-leaving radiance

t_{gv}: absorbing gas transmittance (ozone; sensor view path)

t_{gv}: absorbing gas transmittance (ozone; solar path)

f_p: sensor polarization sensitivity correction factor

Aerosol Models for Atmospheric Correction

• Gordon & Wang’s aerosol models based on Shettle and Fenn’s (1979) models for tropospheric and oceanic aerosols

-Twelve (12) aerosol models are used in operational processing (#’s refer to relative humidity)

-Oceanic

O99

-Maritime (1% oceanic and 99% tropospheric)

M99, M90, M70, M50

-Coastal (0.5% oceanic and 99.5% tropospheric)

C99, C90, C70, C50

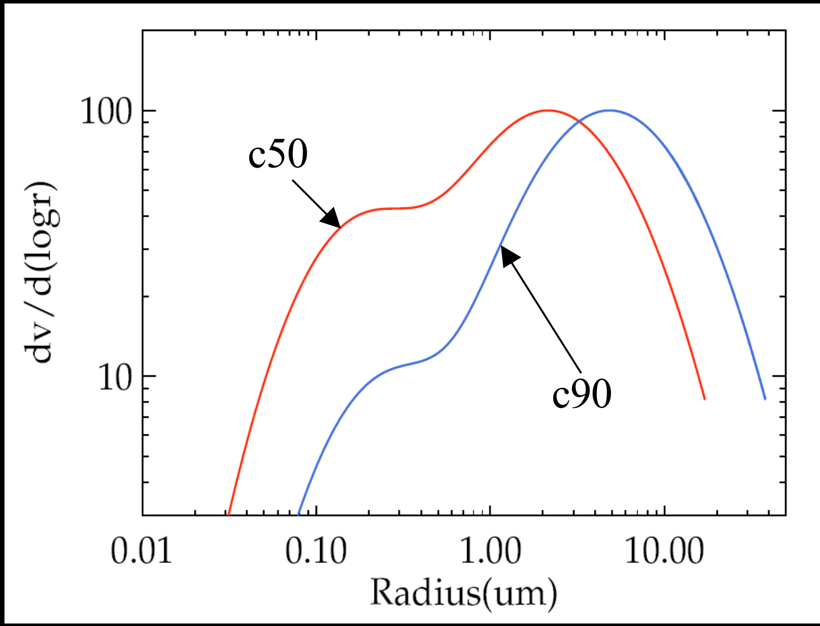
-Tropospheric

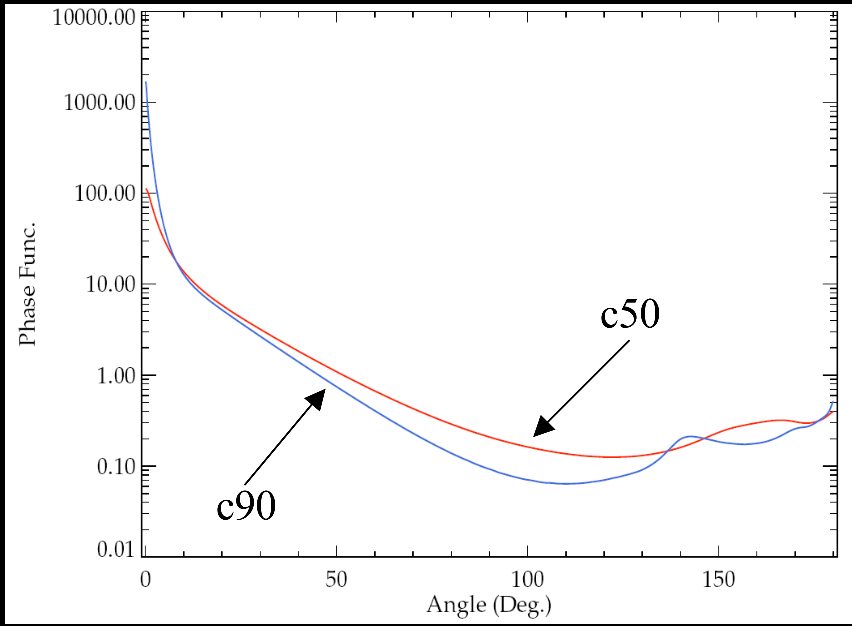
T99, T90, T50

Some Properties of G&W Aerosol Models

Size Distribution

Phase Function

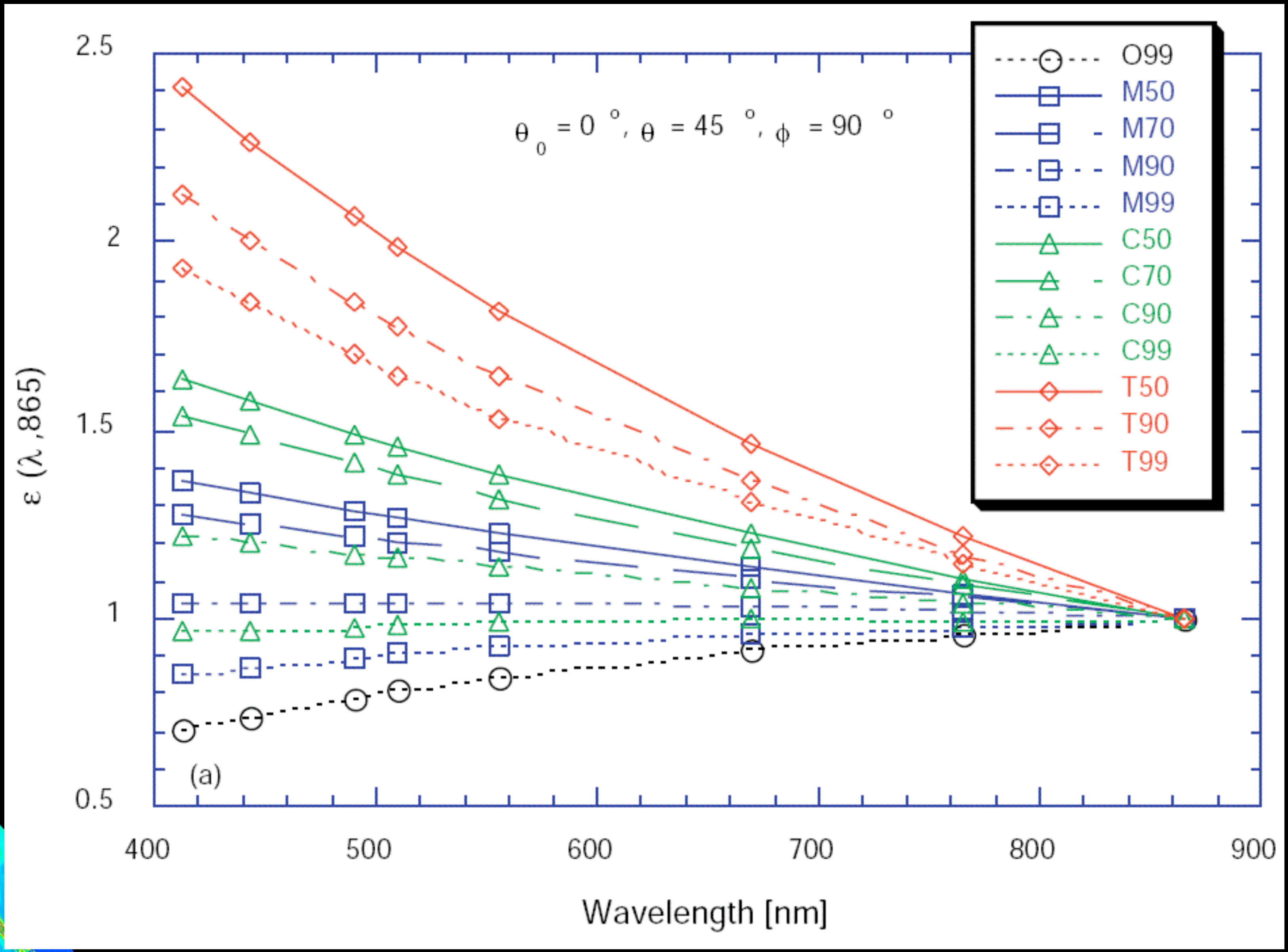




- Effective radius varies from 0.14 to 4.74 _m
- Single Scattering Albedo (SSA) varies from 0.93 (T50) to 1.0 (O99)

Epsilons for 12 Models

Solar Zenith = 0º, Sensor Zenith = 45º, Sensor Azimuth = 90º



Computations of _ $\_{,865}$ and _ $\_{, atm}$ Reflectances

- Convert the observed 765- and 865-nm reflectances into single scattering reflectances and compute $\_{765, 865}$ (obs, ss).

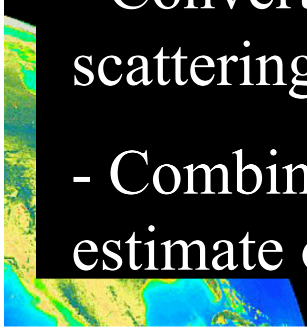
-Convert LUT multiple-scattering reflectances into single scattering reflectances using multiple to single scattering coeffs. and compute $\_{765, 865}$ (cal, ss) for each aerosol model.

- Select two models that bracket the observe $\_{765, 865}$. Also, compute _ $\_{, 865}$ (cal, ss) for both models.

- Since _ $\_{, 865}$ (cal, ss) =[_ $\_$ (cal, ss)/ $\_{865}$ (cal, ss)]$_{LUT}$ = [_ $\_$ (obs, ss)/ $\_{865}$ (obs, ss)], compute _ $\_$ (obs, ss)

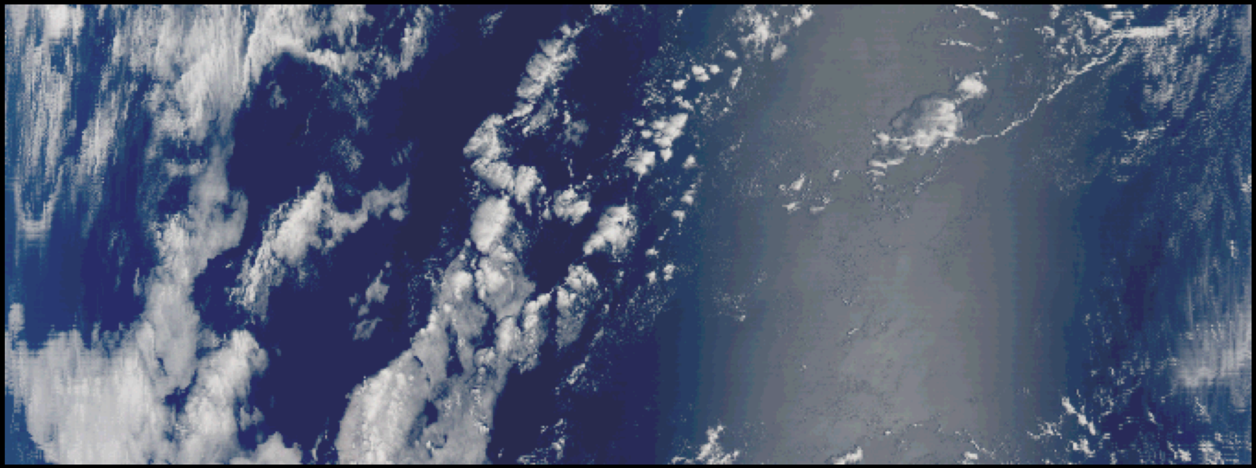
- Convert _ $\_$ (obs, ss) into _ $\_{obs}$ (obs, ms) using single to multiple scattering coeff.

- Combine _ $\_$ (obs, ms) from the two distributions to get the best estimate of _ $\_{, atm}$



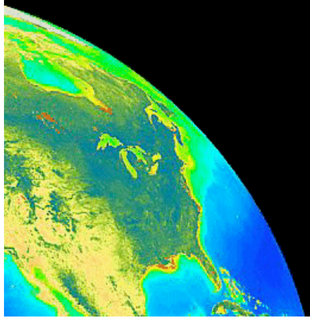
Surface Effects

Sun Glint



White Caps

Corrections based on statistical models (wind & geometry)

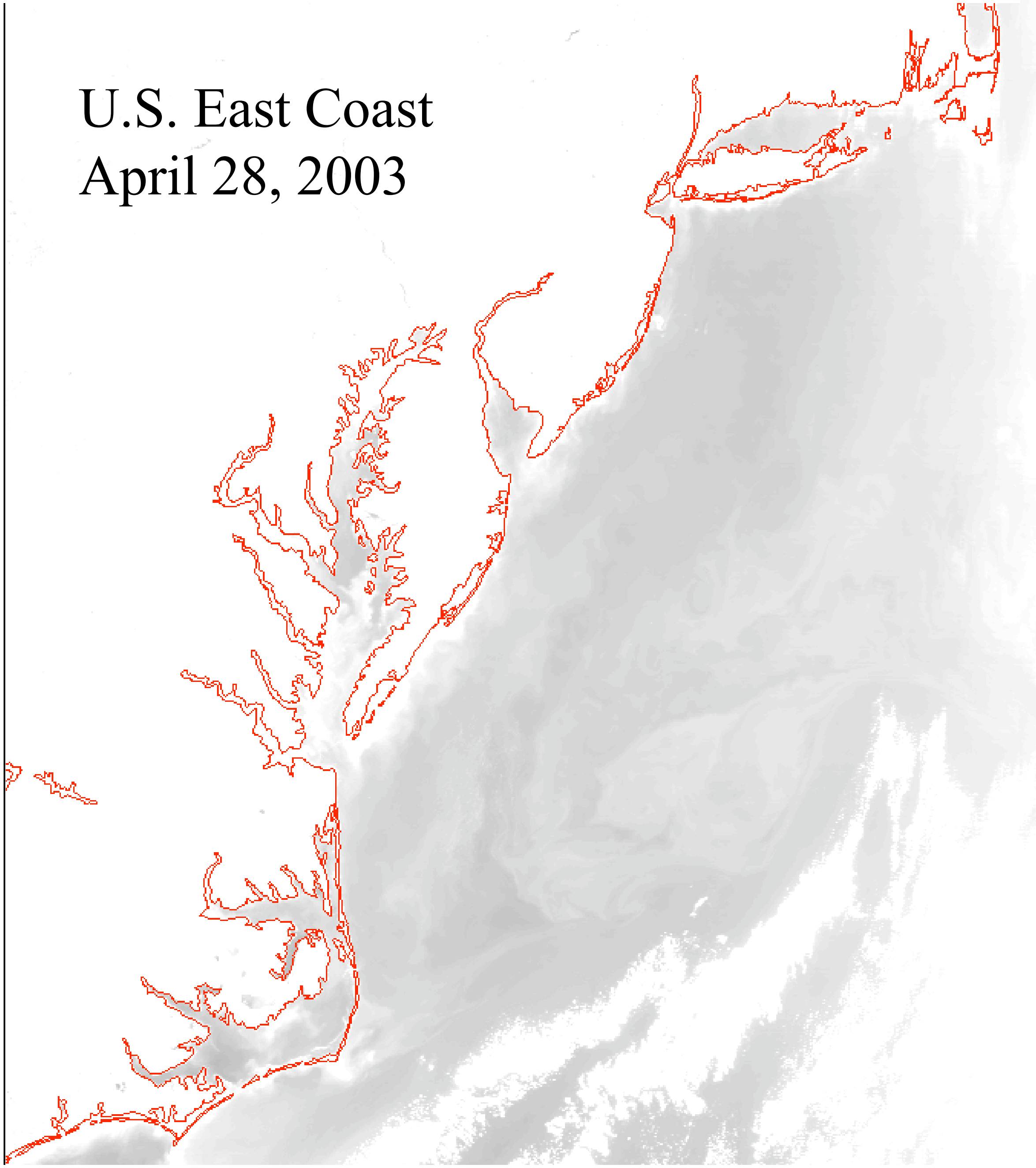


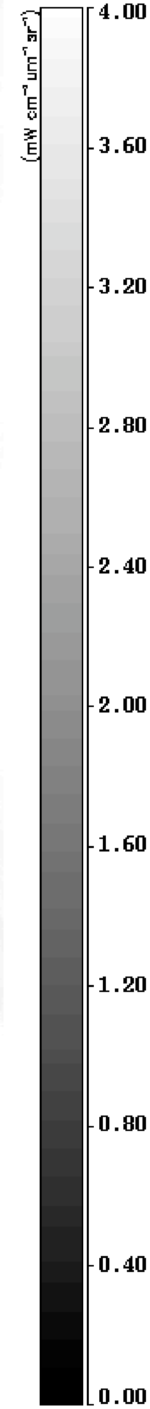
Atmospheric Correction: An Example

Green wavelength
551 nm

Total top-of-the-atmosphere radiance

$0 - 4 \ ^{mW}\!/_{cm^2 \ sr \ \mu m}$

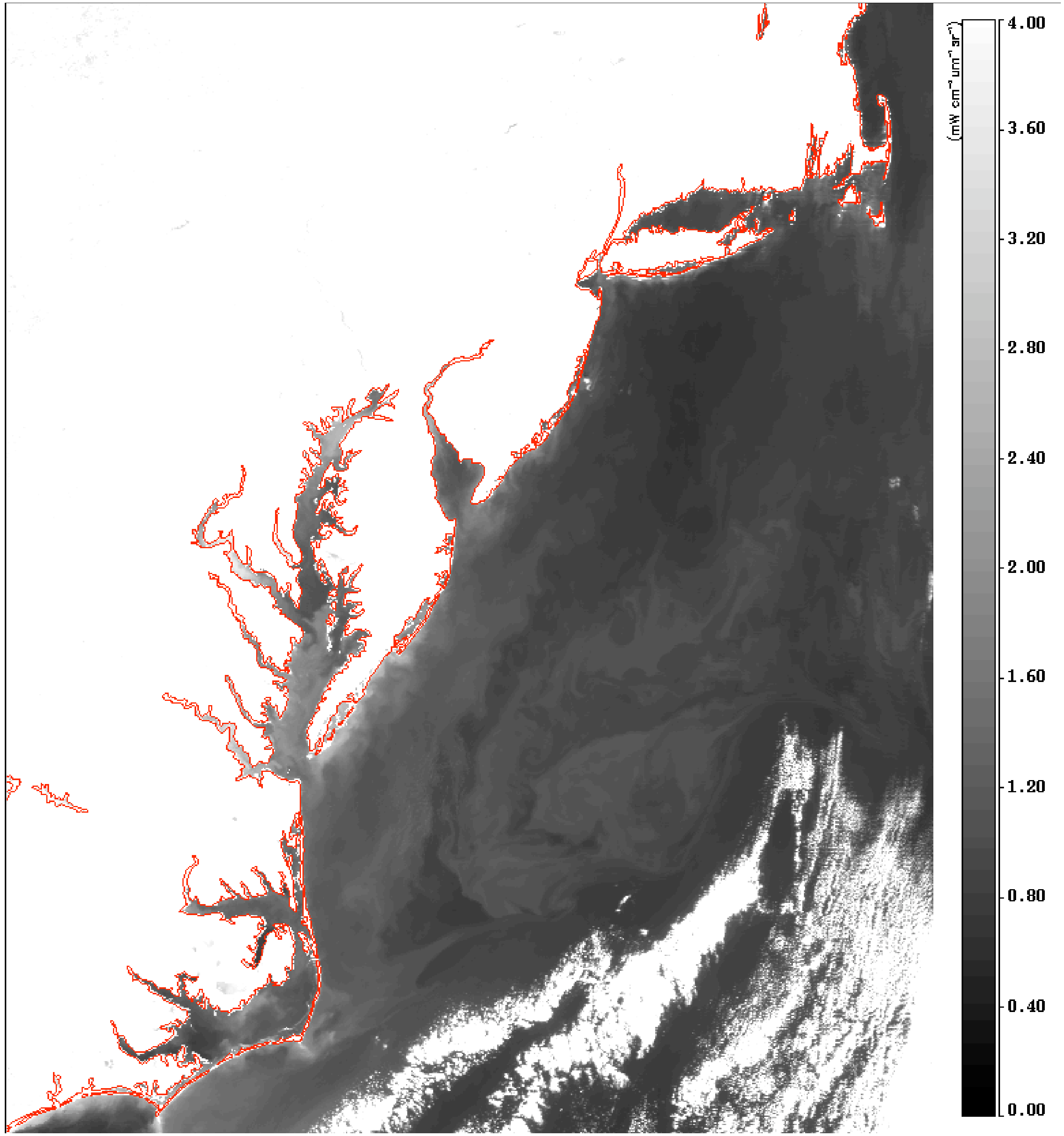




Green wavelength
551 nm

Total top-of-the-atmosphere radiance corrected for ozone absorption and Rayleigh (gas molecule) scattering

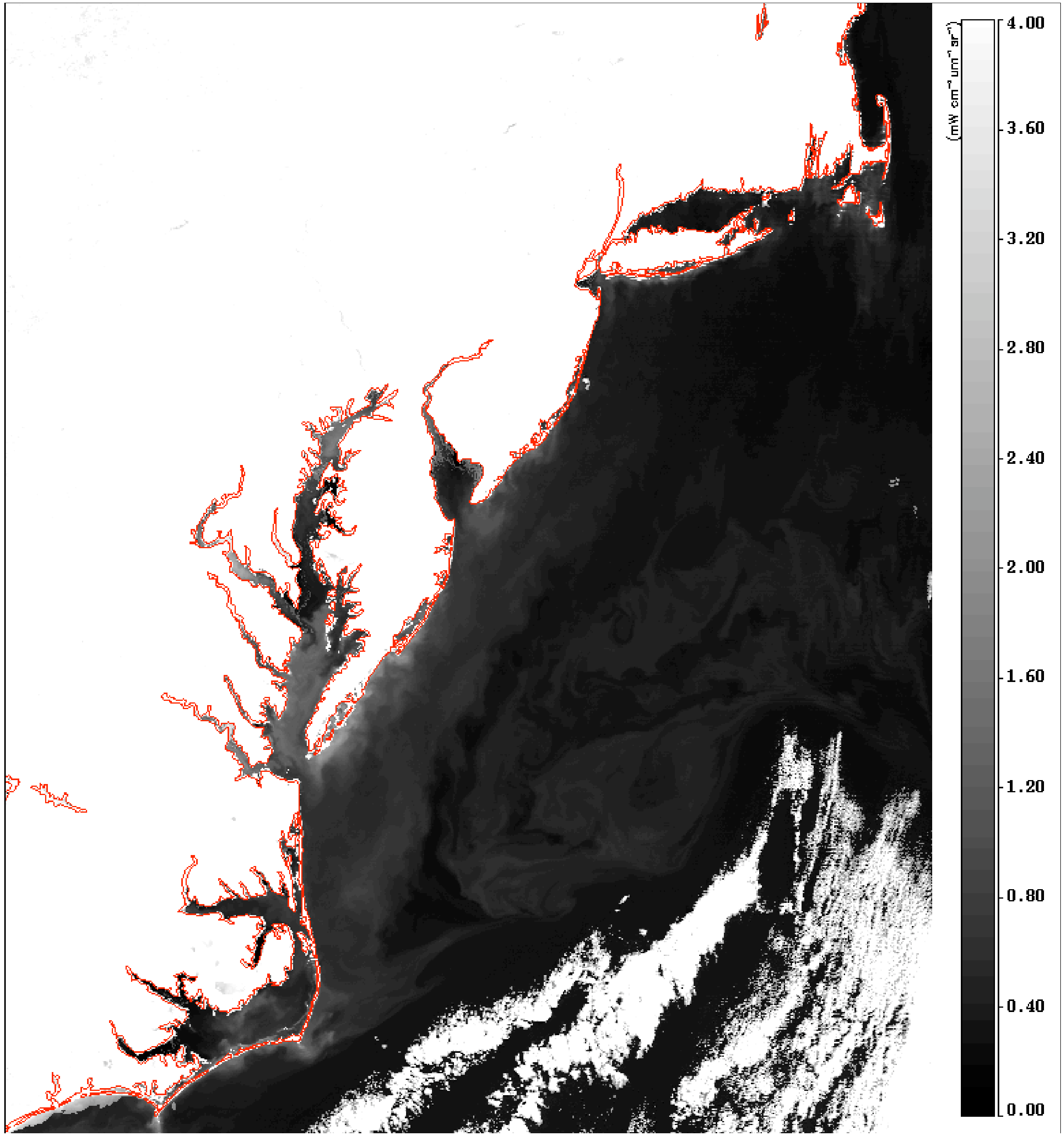
$0 – 4 \ {}^{mW}\!/_{cm^2\ sr\ \mu m}$



Green wavelength
551 nm

Total top-of-the-atmosphere radiance corrected for ozone absorption, Rayleigh & aerosol scattering

$0 - 4 \; \frac{mW}{cm^2 \; sr \; \mu m}$

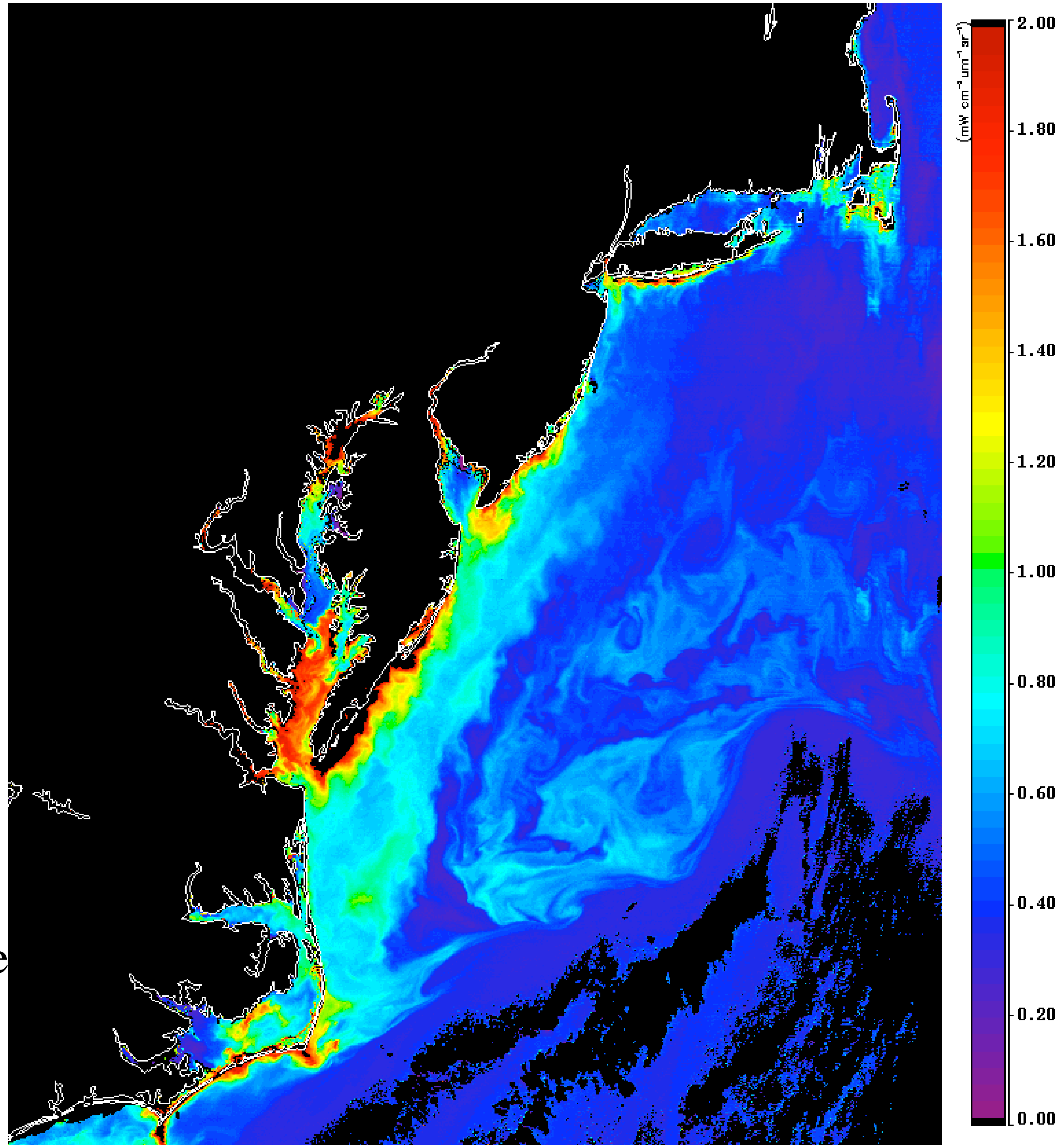


Green wavelength
551 nm

<u>Normalized</u> water-leaving radiance

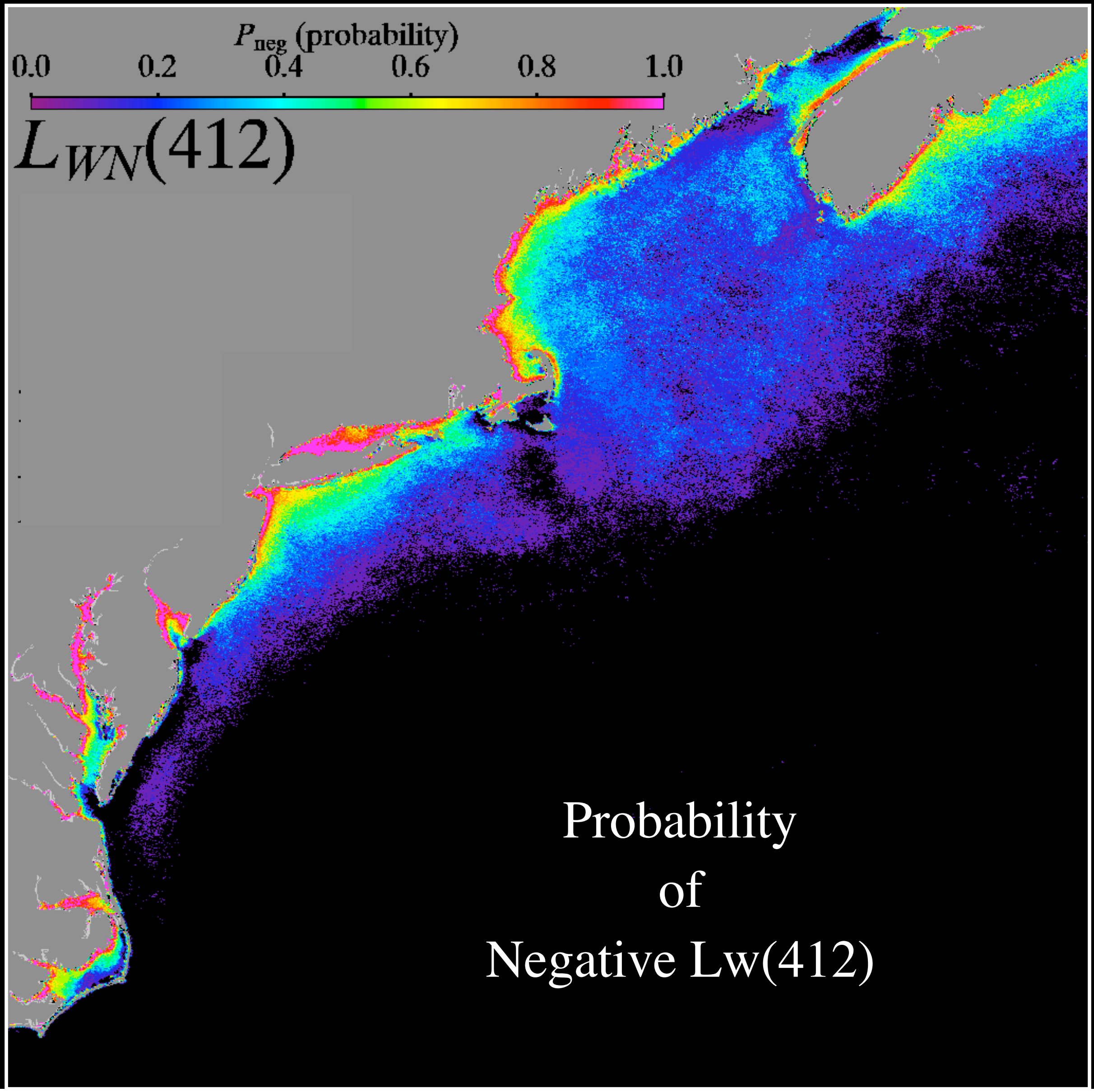
$0 - 2 \ {}^{mW}\!/\!_{cm^2\ sr\ \mu m}$

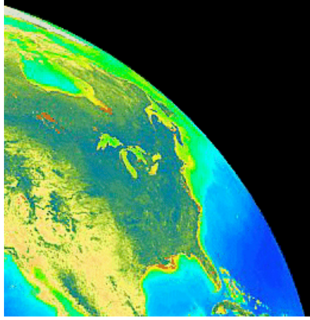
Normalized: Lw is transformed to radiance normal to the surface taking into account the ocean BRDF



Atmospheric Correction: Negative Lw's

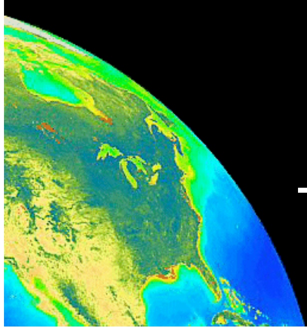
Certain coastal regions (e.g., NE U.S. & Southern California) are problematic due to aerosol types not represented in model suite & lack of NO_2 correction.





NIR Calibration Strategy

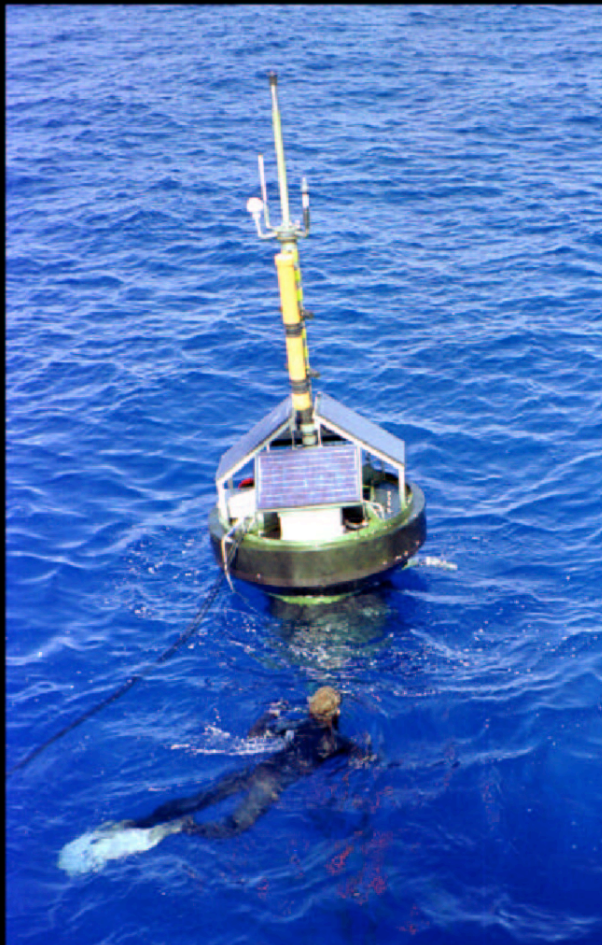
- Assume 865 & 869 (SeaWiFS, MODIS) nm calibrations after temporal degradation corrections are accurate
  - Visible band vicarious calibration insensitive to NIR calibration errors < 5%
- Assume a fixed aerosol type/model for South Pacific and South Indian Ocean sites and adjust 765 & 748 nm band gains to yield "correct" aerosol radiance
  - The "M90" model (Gordon & Wang, 1994)
    - Properties similar to those inferred from the Tahiti AERONET site
  - Gain adjustment magnitude ~ 2-3% for SeaWiFS



Vicarious Calibration: Visible

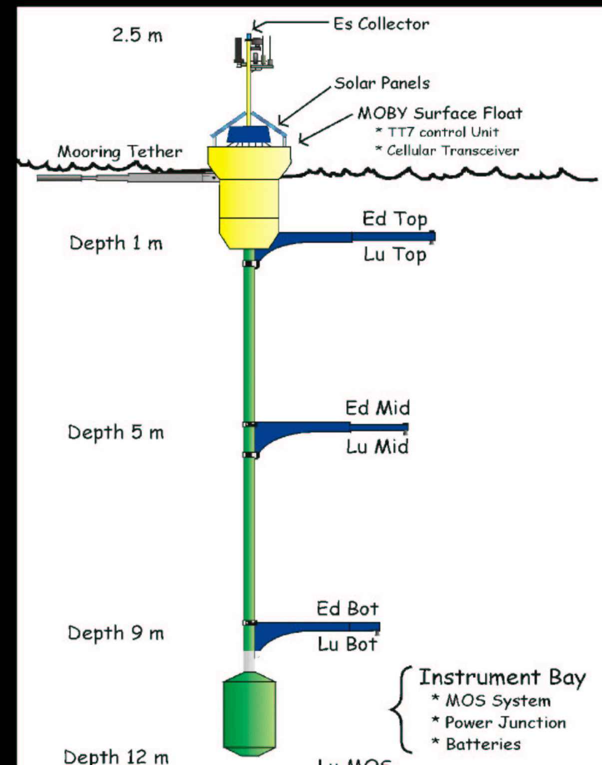
- Match satellite observations with surface L_w's
- Apply atmospheric correction scheme
  - Determine aerosol properties
- Propagate L_w's to top of atmosphere to estimate a "correct" L_t
- Compute calibration gain factor as ratio of "correct" L_t / measured L_t
- Average individual gain factors to produce mission-average gain factor

Vicarious Calibration: Visible

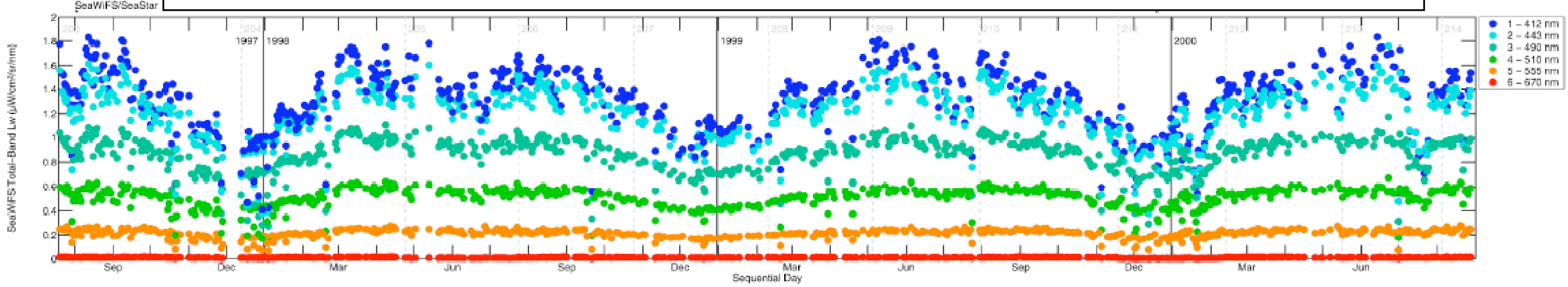


Marine Optical Buoy:
- Deep, clear water site (Lanai, Hawaii)
- Marine atmosphere
- Relatively cloud free
- Low latitude: year-round satellite coverage at useful viewing geometries

- Glint contamination – nontilting sensors



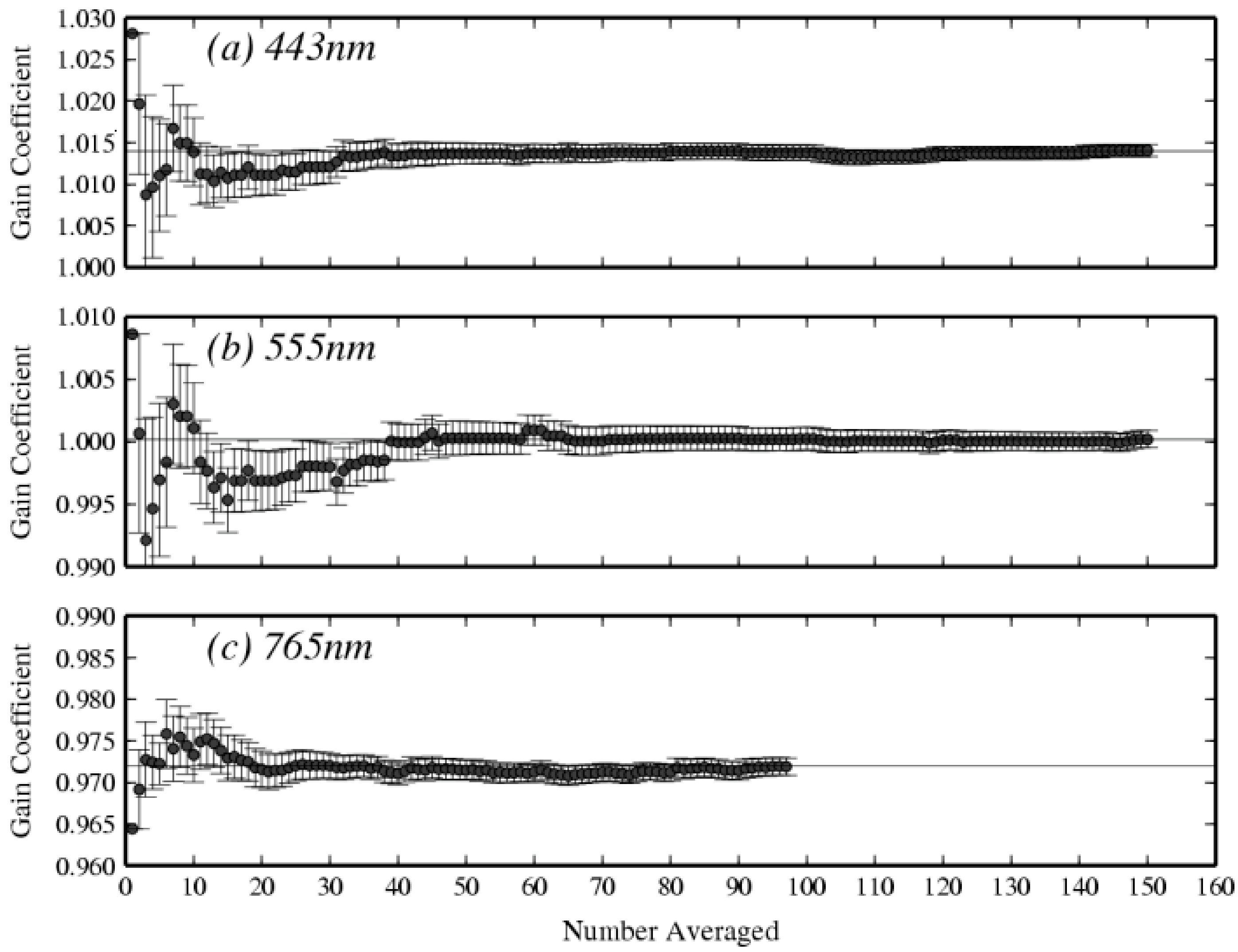
MOBY Water-leaving Radiance Time Series (1997-2000)



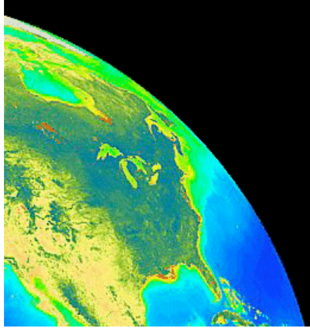
Vicarious Calibration Gain Convergence

- Only a small % of samples result in a MOBY-satellite "match-ups" for the vicarious calibration.

- For MODIS, took over 2 years to collect enough match-ups to derive gain corrections.



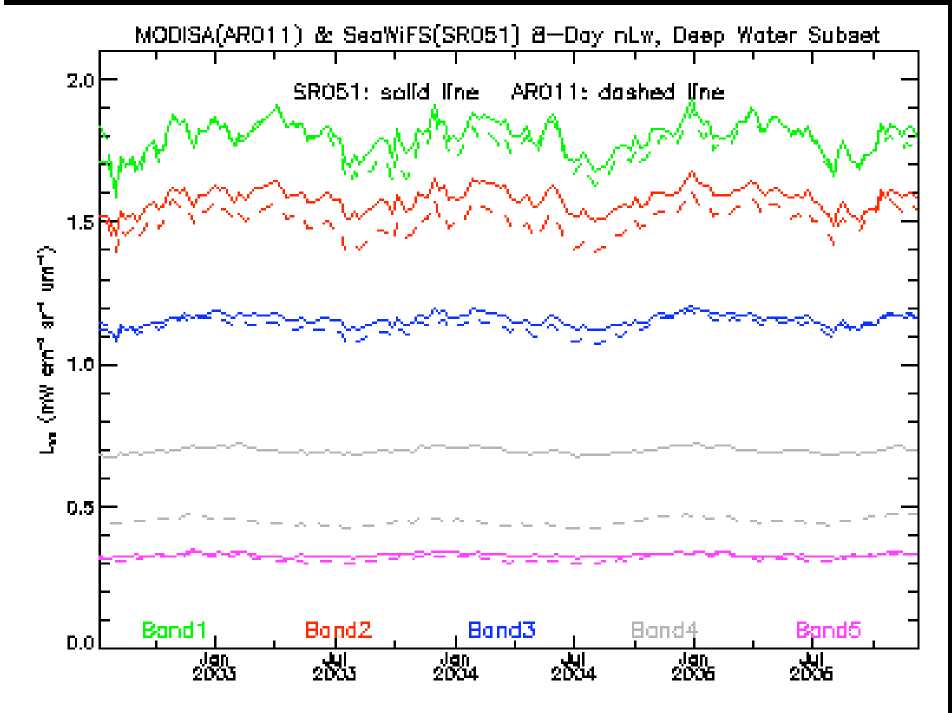
B. A.Franz, S. W. Bailey, P. J. Werdell, and C. R. McClain, "Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry," Appl. Opt. 46, 5068-5082 (2007)



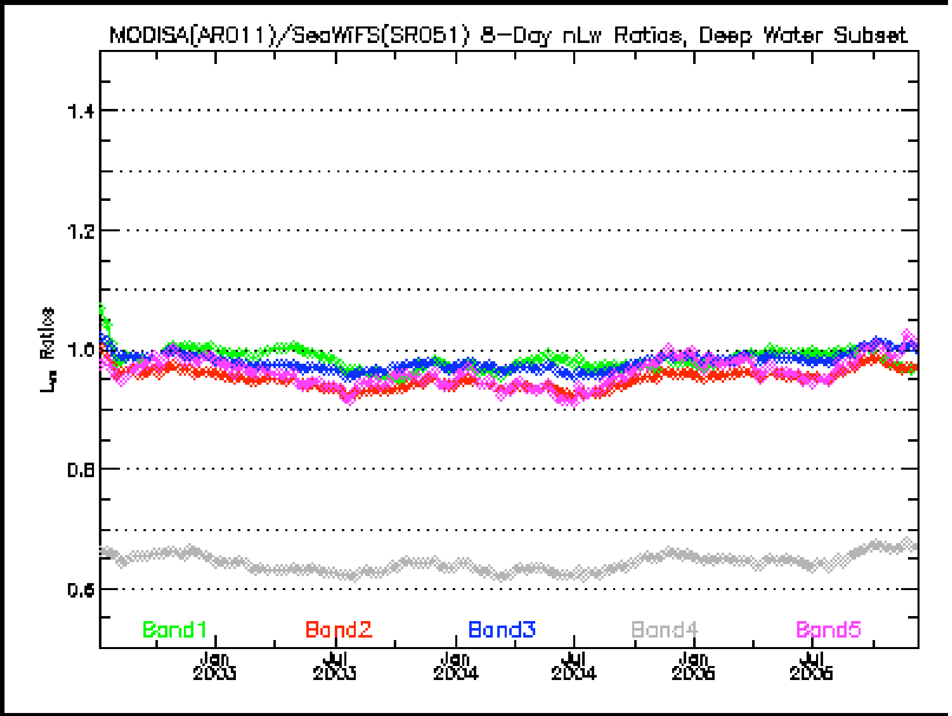
Direct Comparison of Satellite Lwn Retrievals

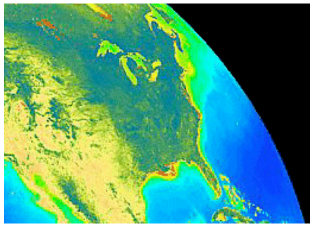
Global Deep-Water, 8-Day Composites, Common Bins

SeaWiFS & MODIS-Aqua



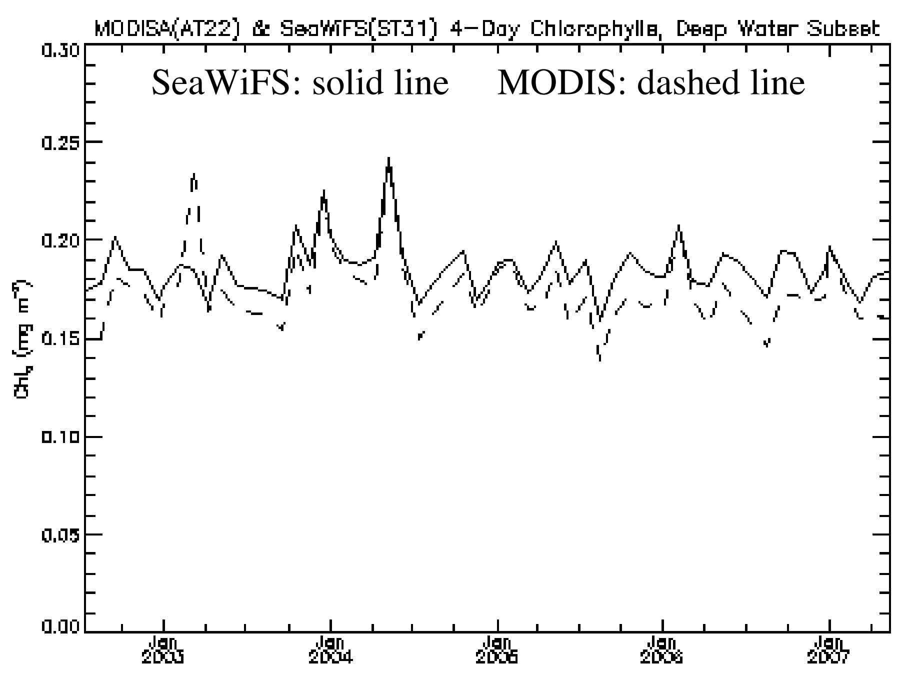
MODIS-Aqua / SeaWiFS

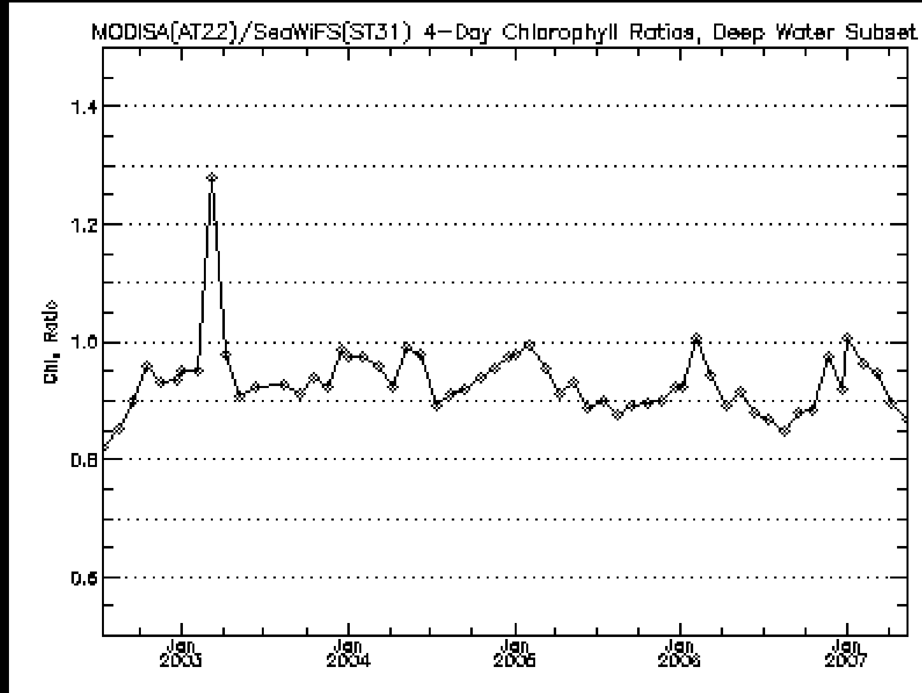




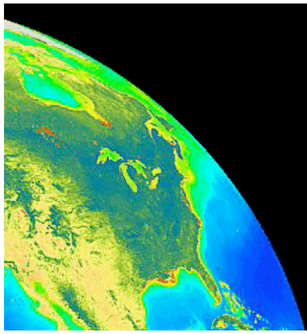
SeaWiFS-MODIS/Aqua Chl-a

Global Deep-Water* Means (2002-2007)

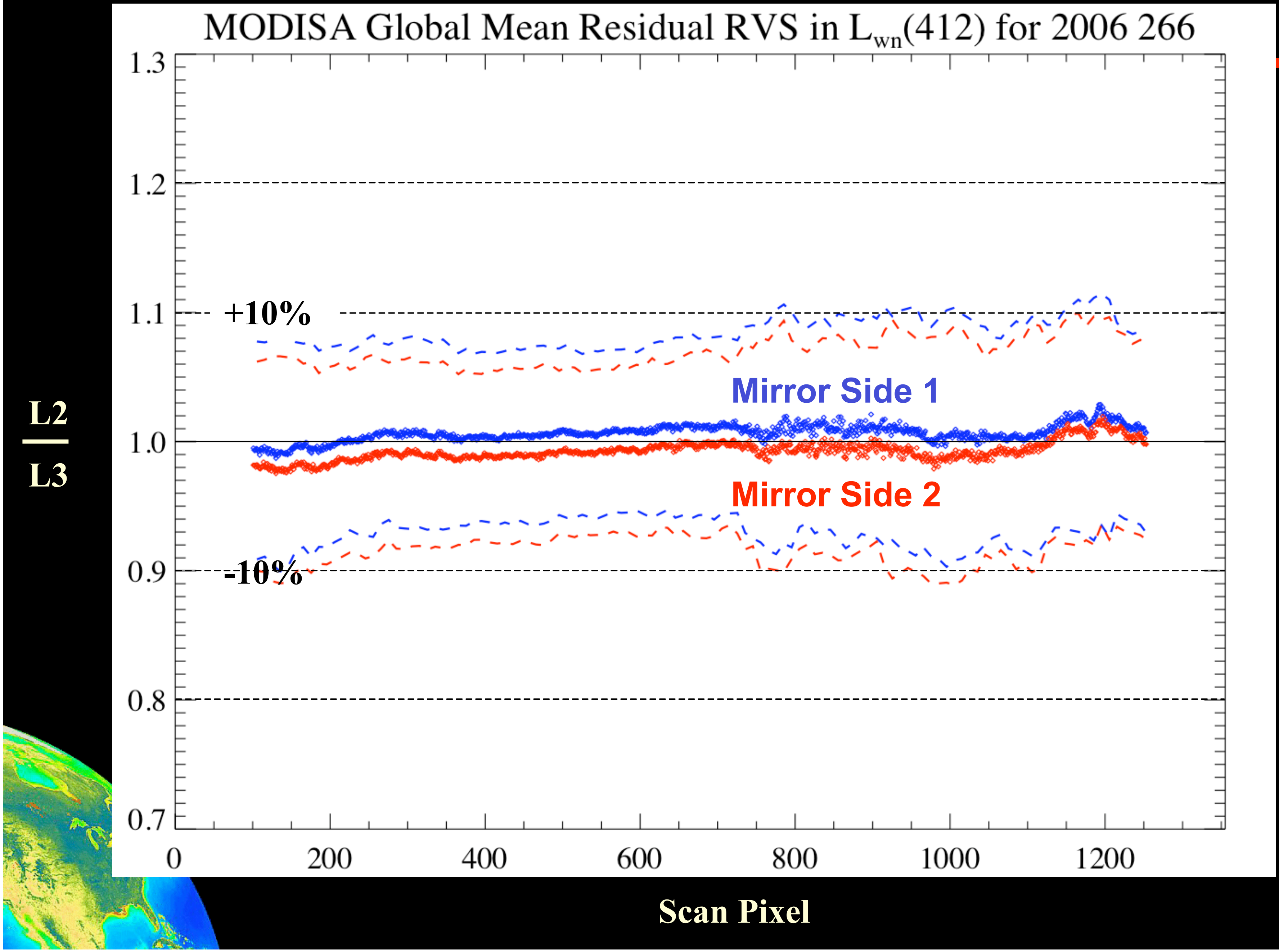




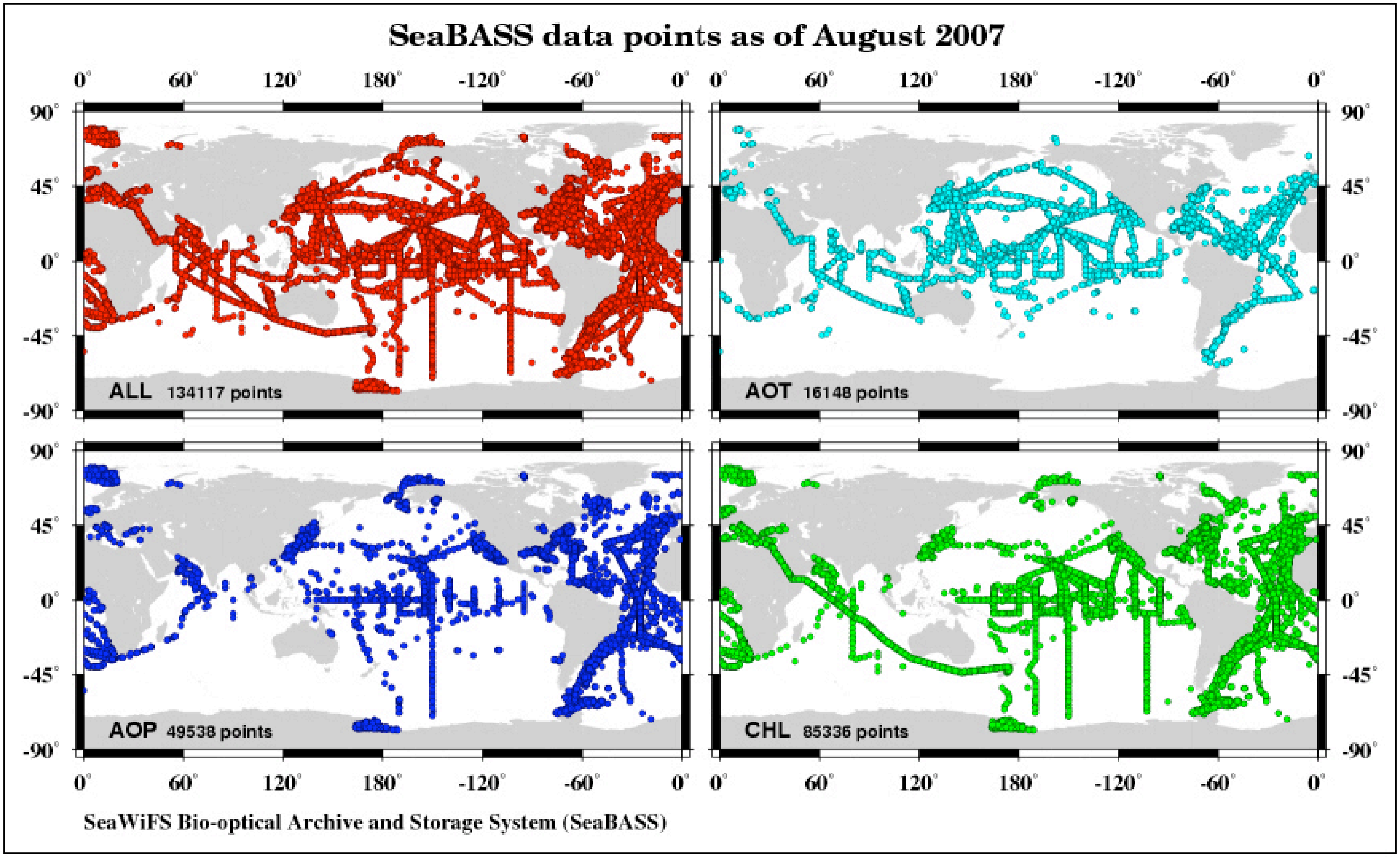
Ratio: MODIS-Aqua/SeaWiFS



MODIS-Aqua Residual RVS - Lwn(412)



SeaWiFS Bio-optical data Archive & Storage System (SeaBASS)



Data from over 1750 cruises

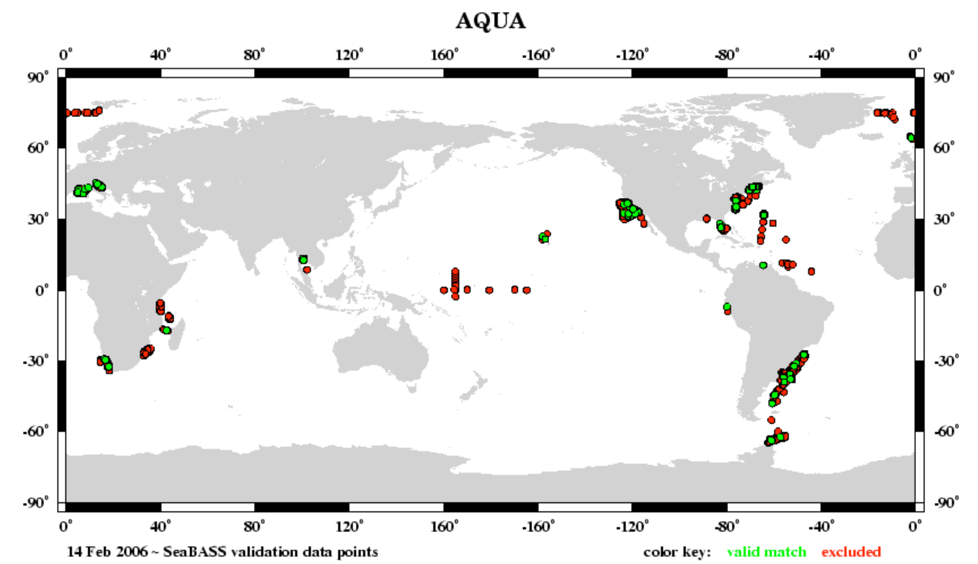
Apparent Optical Property (AOP); Chlorophyll-a (CHL); Aerosol Optical Thickness (AOT)

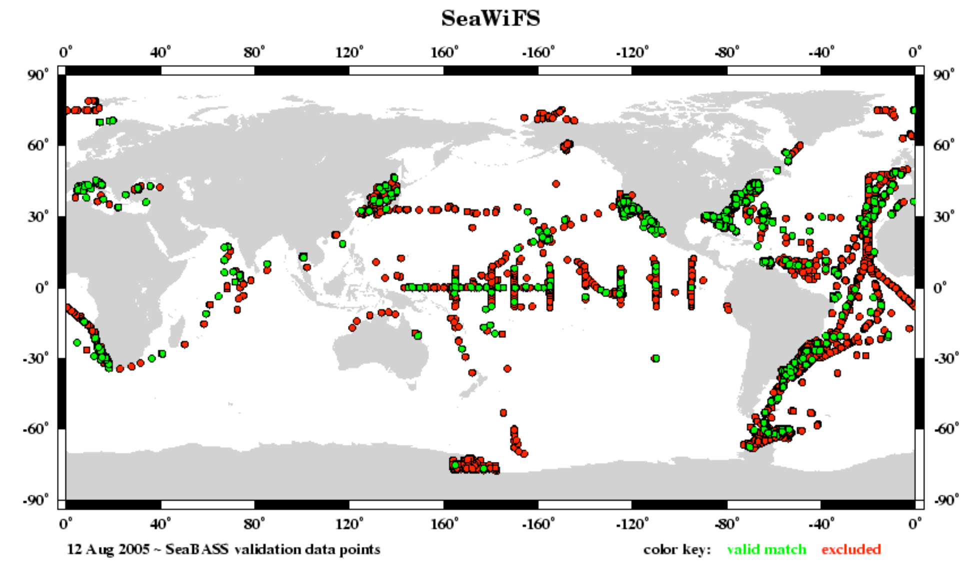
Available *In Situ* Match-Ups by Mission

MODIS/Aqua July 2002 - Present

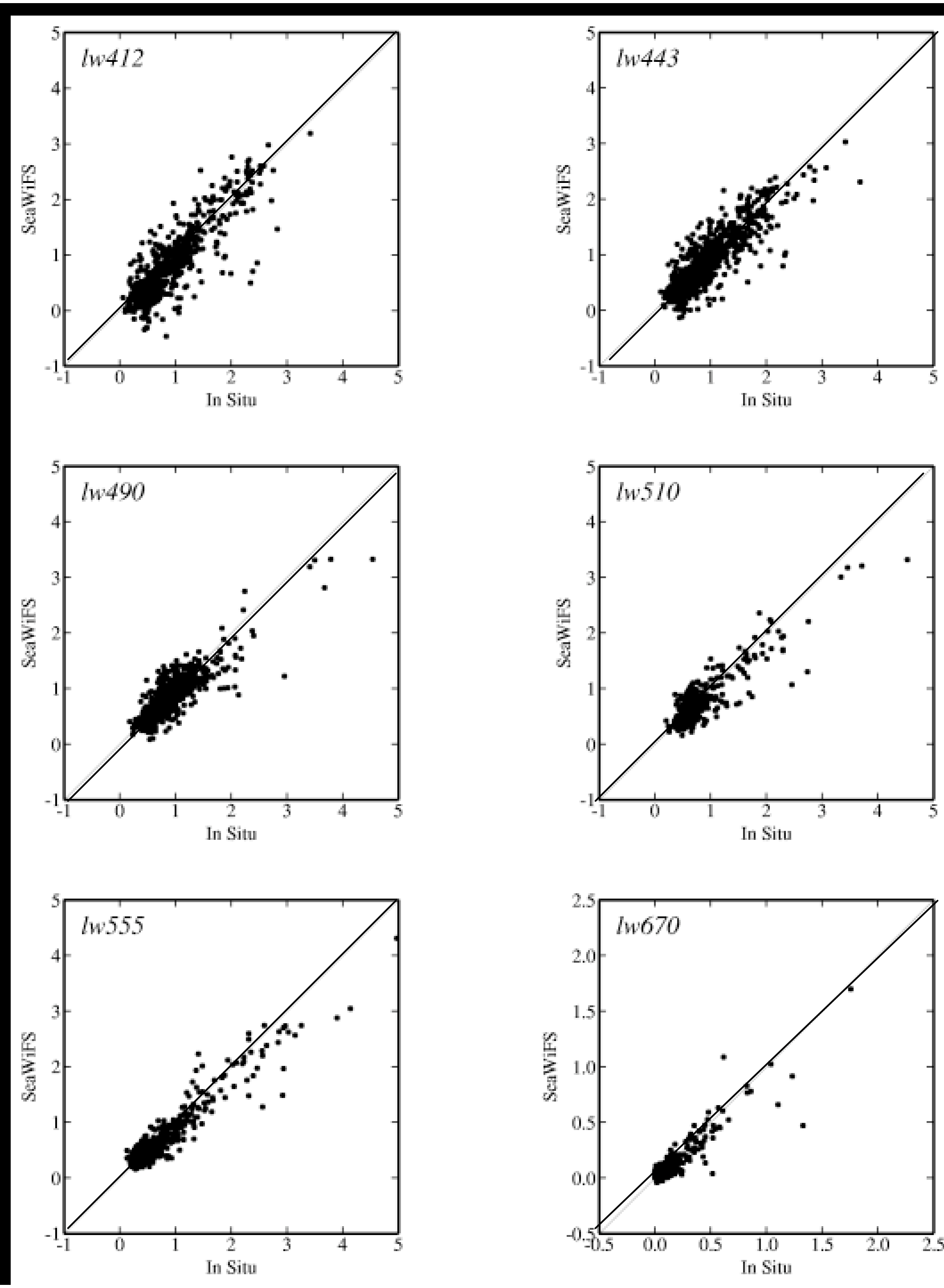
Roughly 10% of stations pass match-up criteria

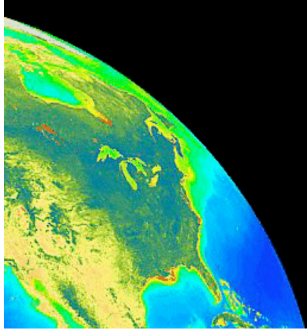
SeaWiFS Sept 1997 - Present



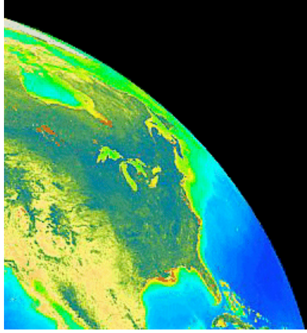


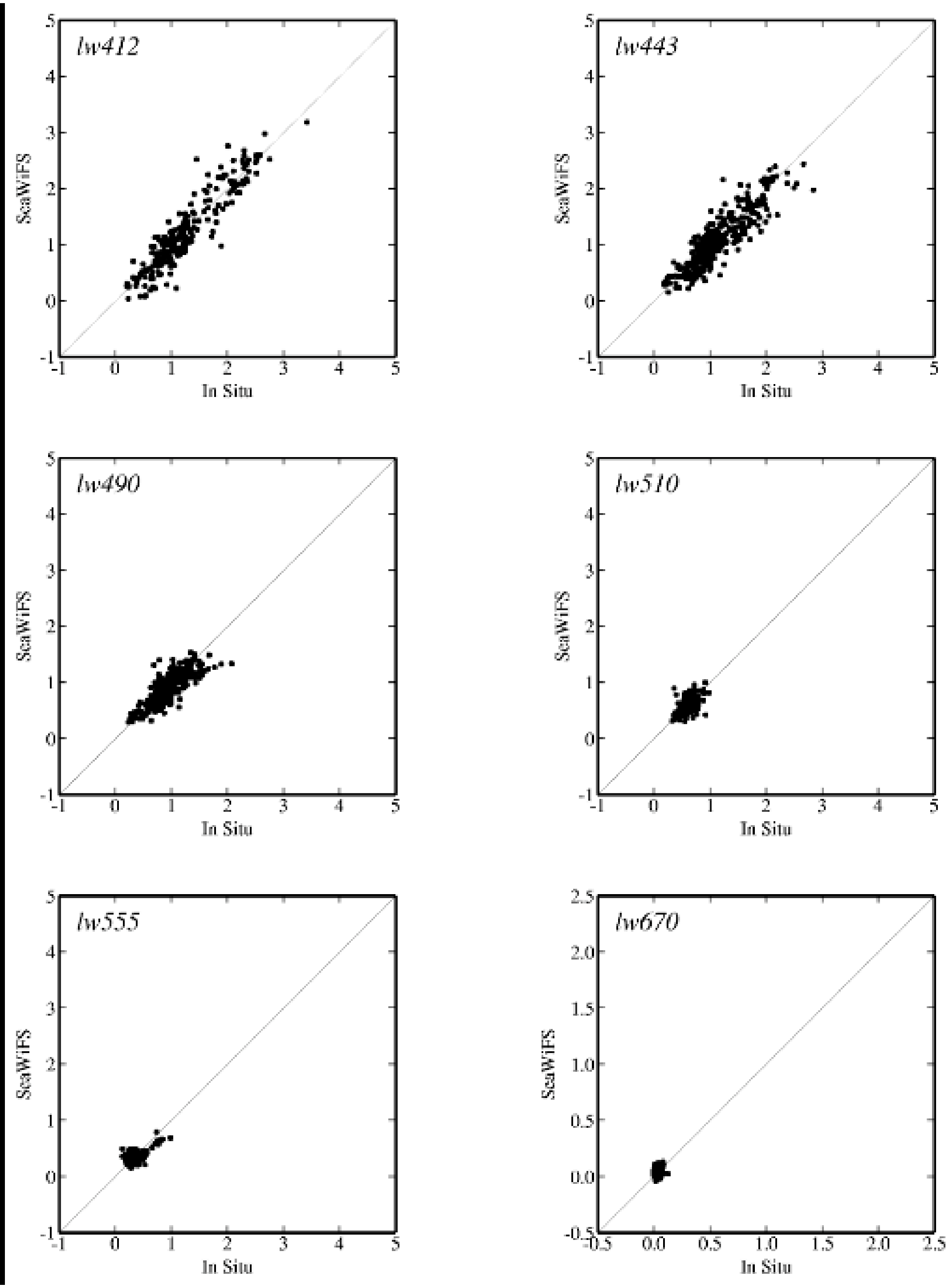
SeaWiFS Lwn Comparisons with Field Data



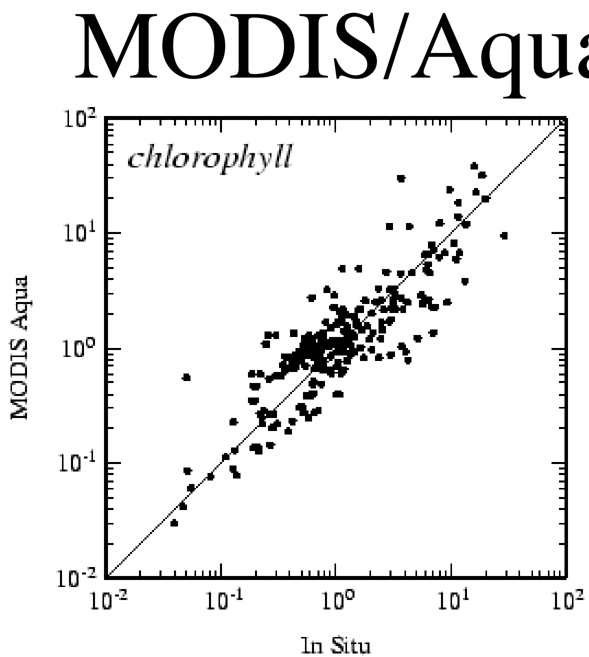


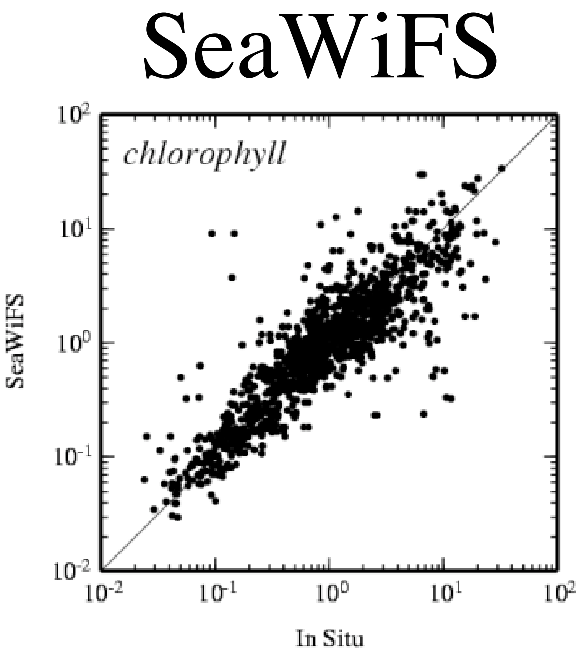
SeaWiFS Lwn Comparisons with Field Data: Deep Water Only (> 1000 m)





Comparison of Chlorophyll Retrievals to *In Situ*



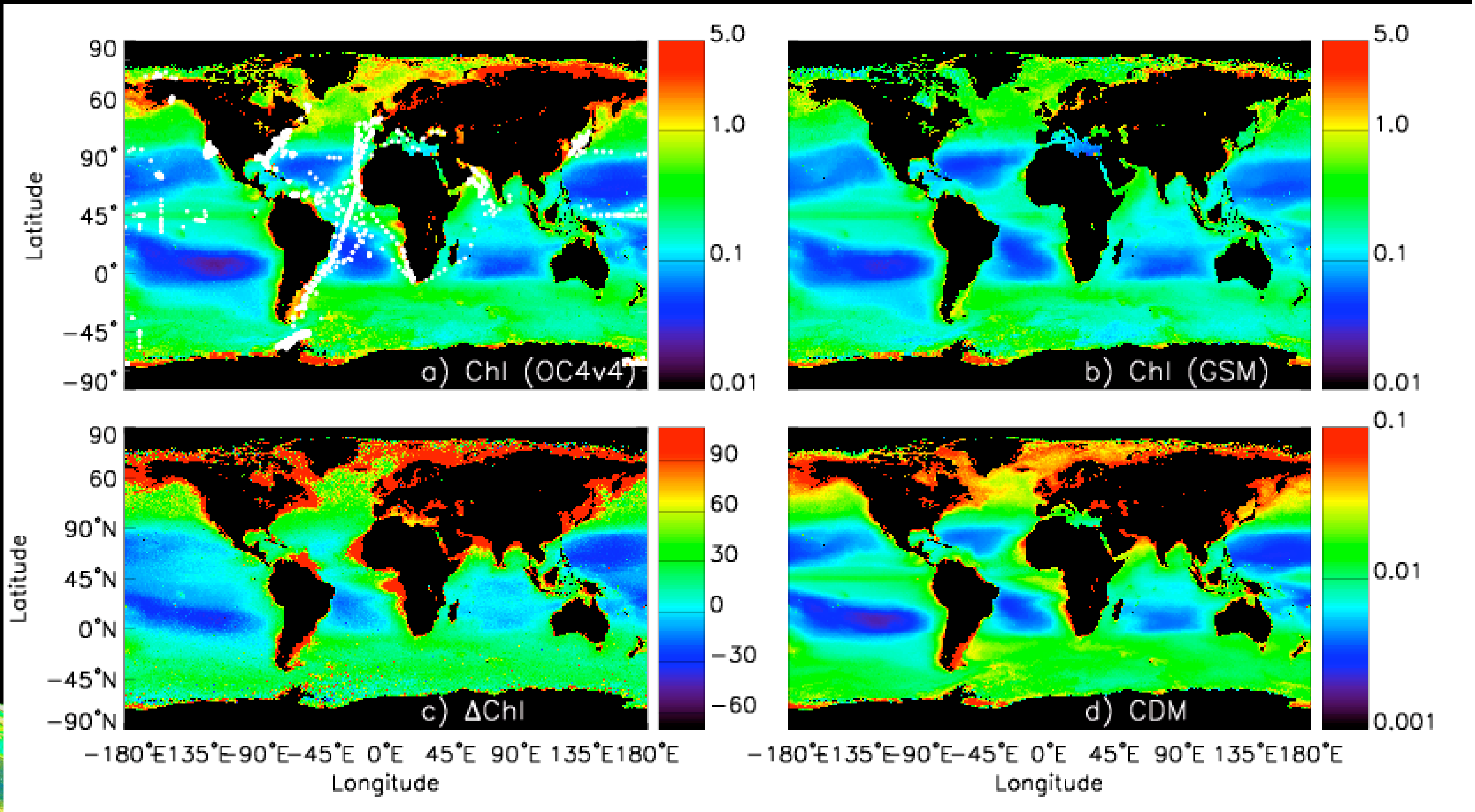


Sensor	# Matches	Mean Ratio	% Diff	r^2
SeaWiFS	1293	0.998	33.1	0.796
MODIS/Aqua	263	1.084	40.4	0.780

- Band-ratio algorithms very forgiving of radiometric biases.
- Semi-analytic reflectance inversion models very unforgiving

…<u>required</u> direction of future algorithm development.

Band Ratio (OC4) vs. Semi-analytic (GSM) Algorithms

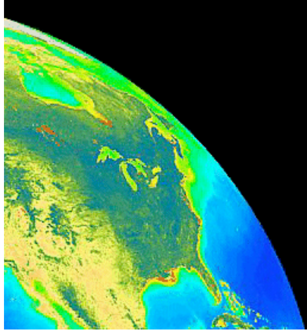


_Chl(%)= 100*[Chl(OC4v4) – Chl(GSM)/Chl(GSM)]

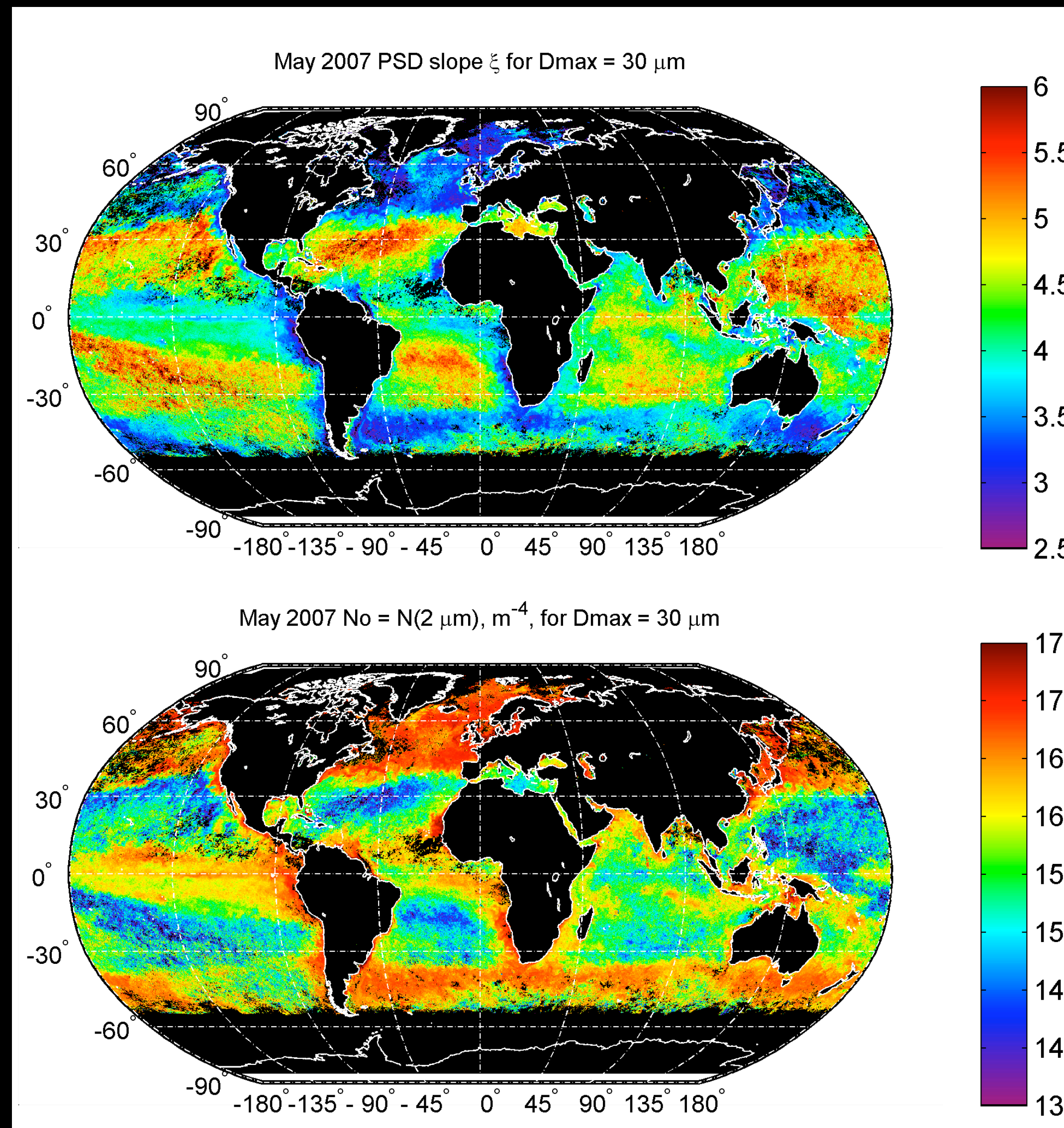
CDM: Colored Dissolved Matter

Semi-analytic Inversion Models: Marine Optical Properties

Marine particle size distribution properties=> phytoplankton functional groups, etc.

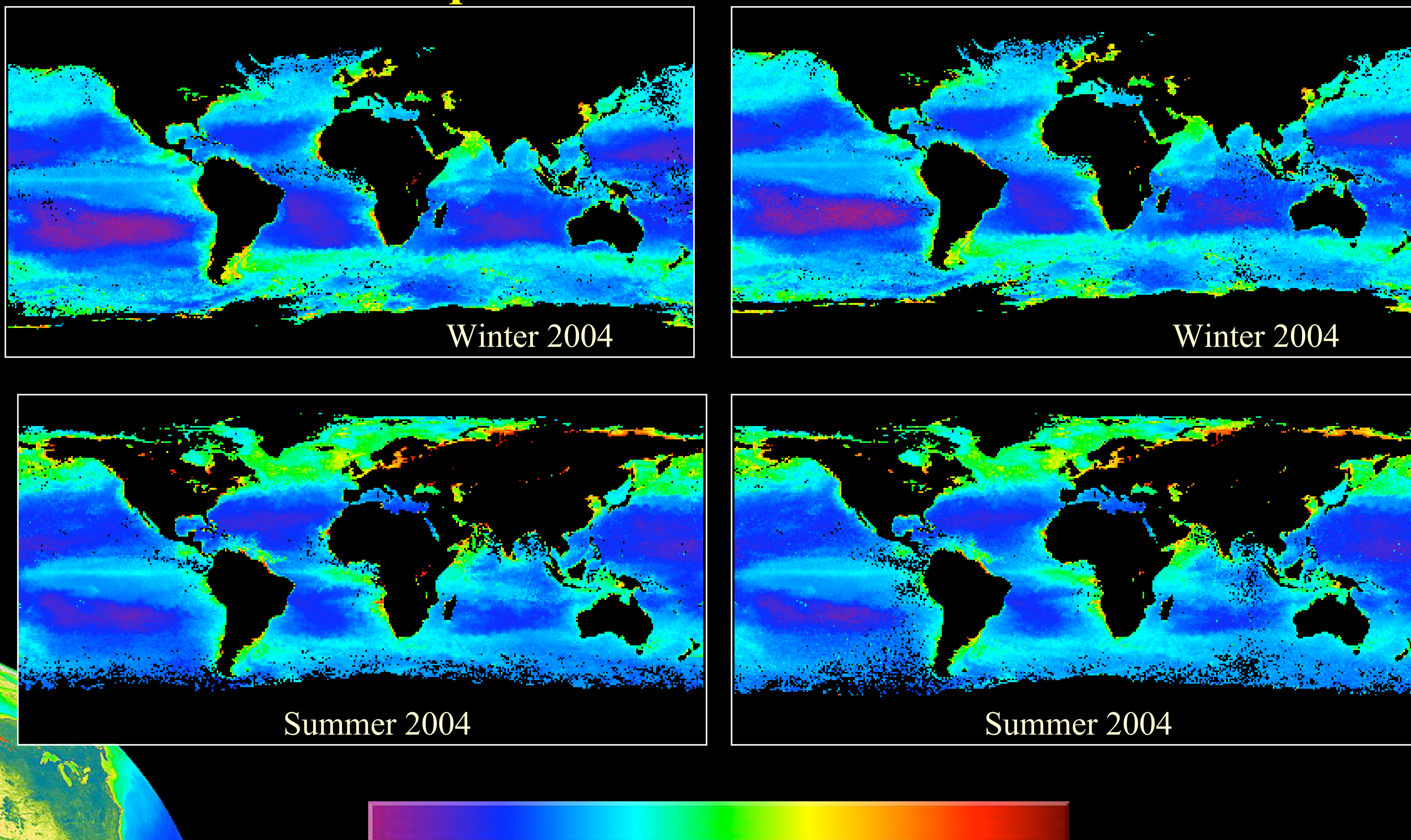


log10(particles/m^{-4})



Seasonal Chlorophyll Images: Comparison across Sensors

MODIS/Aqua | **SeaWiFS**



0.01-64 mg m^{-3}

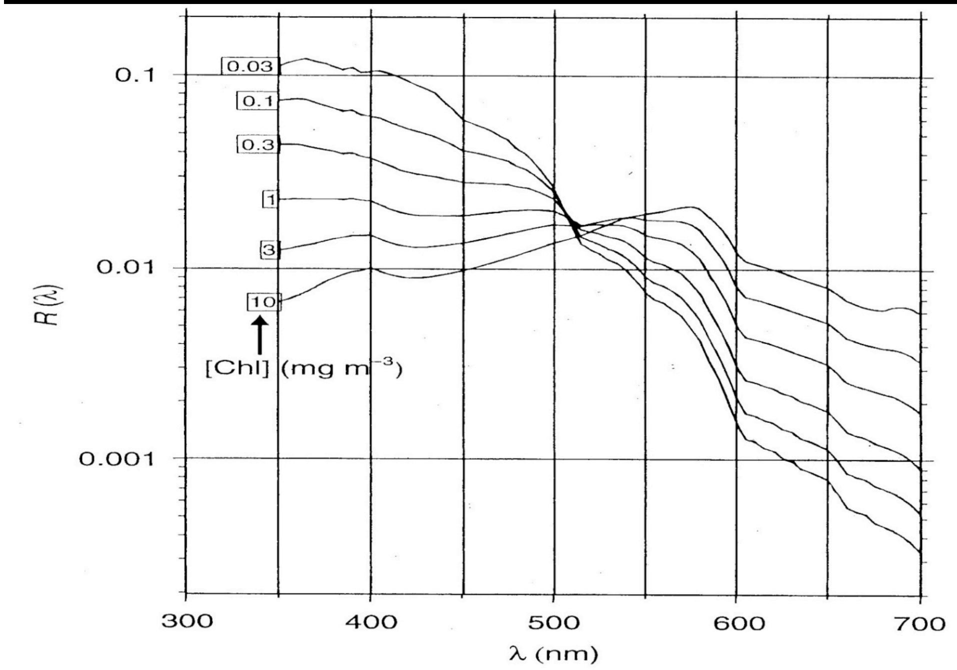
Ocean Reflectance: Open Ocean vs. Turbid Water

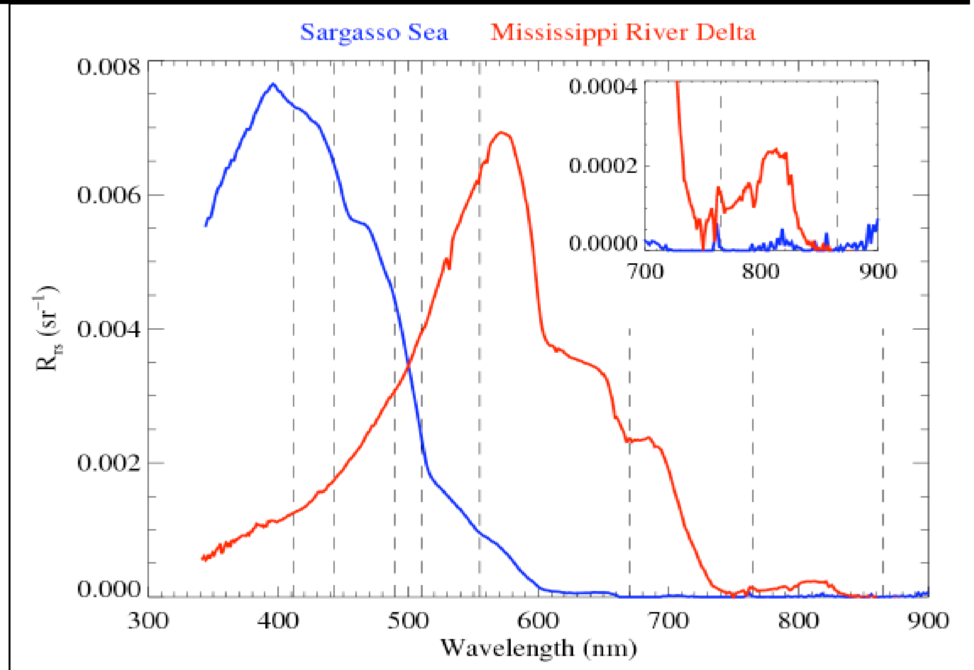
Irradiance Reflectance of the Ocean

R^{0-} (_) $=E_u^{(0-)}$ (_) $/E_d^{(0-)}$ (_)

Remote Sensing Reflectance $Rrs=L_w/E_d^{(0+)}$

Sargasso Sea and Mississippi River Delta





Atmospheric Correction Methodology (cont.)

- NIR Reflectance Correction in Turbid Water

-For higher concentration of chlorophyll (above 0.7 mg/m^3) the assumption that water-leaving radiance (L_w) in the NIR bands is zero is no longer valid. The correction is based on a bio-optical model that relates the remote sensing reflectance (Rrs) in the NIR as:

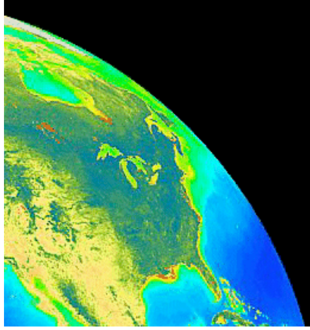
$$R_{rs}(\_) = R_{rs}(\_0)[a_{tot}(\_0)/a_{tot}(\_)][b_b(\_)/b_b(\_0)]–$$

where $\_0$=670-nm, and $\_$=765 and 865 nm

$a_{tot}(\_) = a_w(\_)+ a_{ph}(\_) + a_{dg}(\_)$ absorption coefficients

$b_b(\_) = b_{bw}(\_) + b_{bp}(\_)$ backscattering coefficients

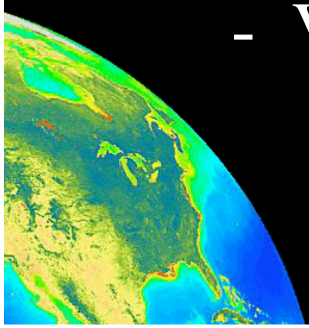
where $b_{bw}(\_) = a(S)\cdot\_^{-4.32}$ and $b_{bp}(\_) = m/\_ + c$



$R_{rs} = L_w / E_d$, where E is the surface solar irradiance.

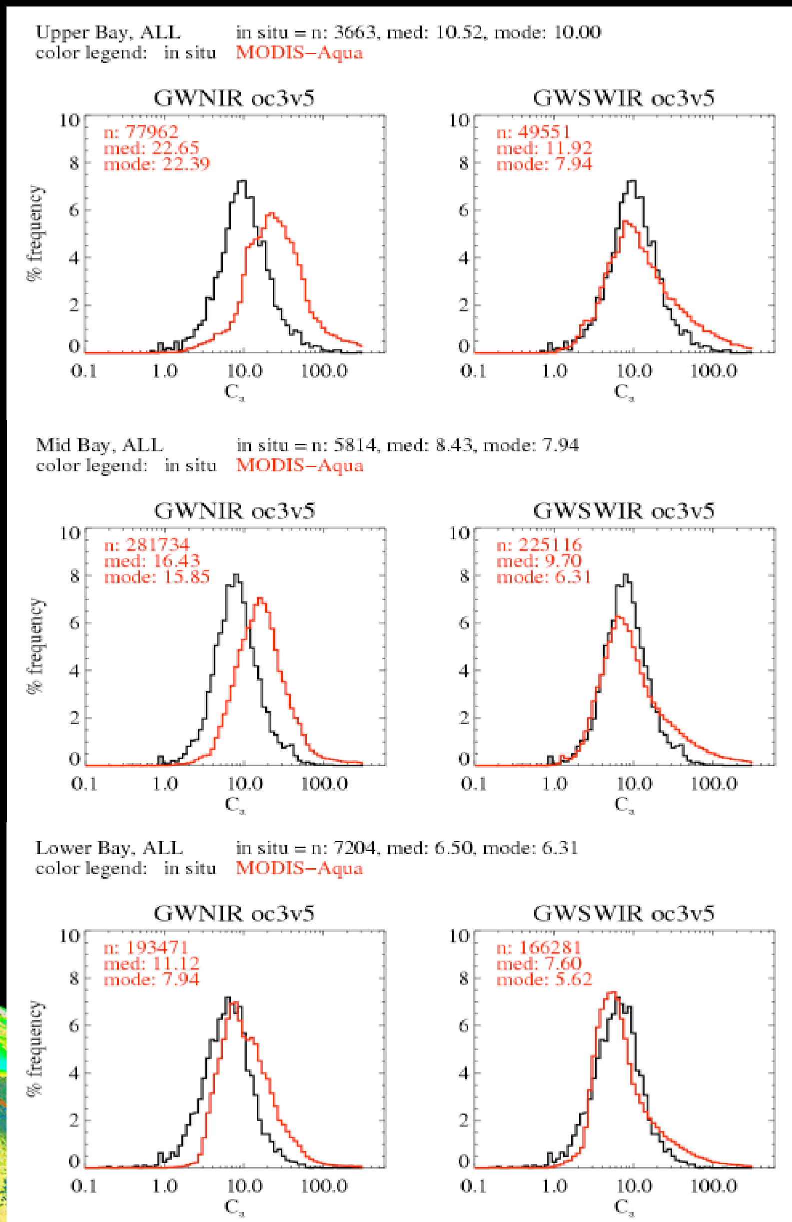
Atmospheric Correction Methodology (cont.)

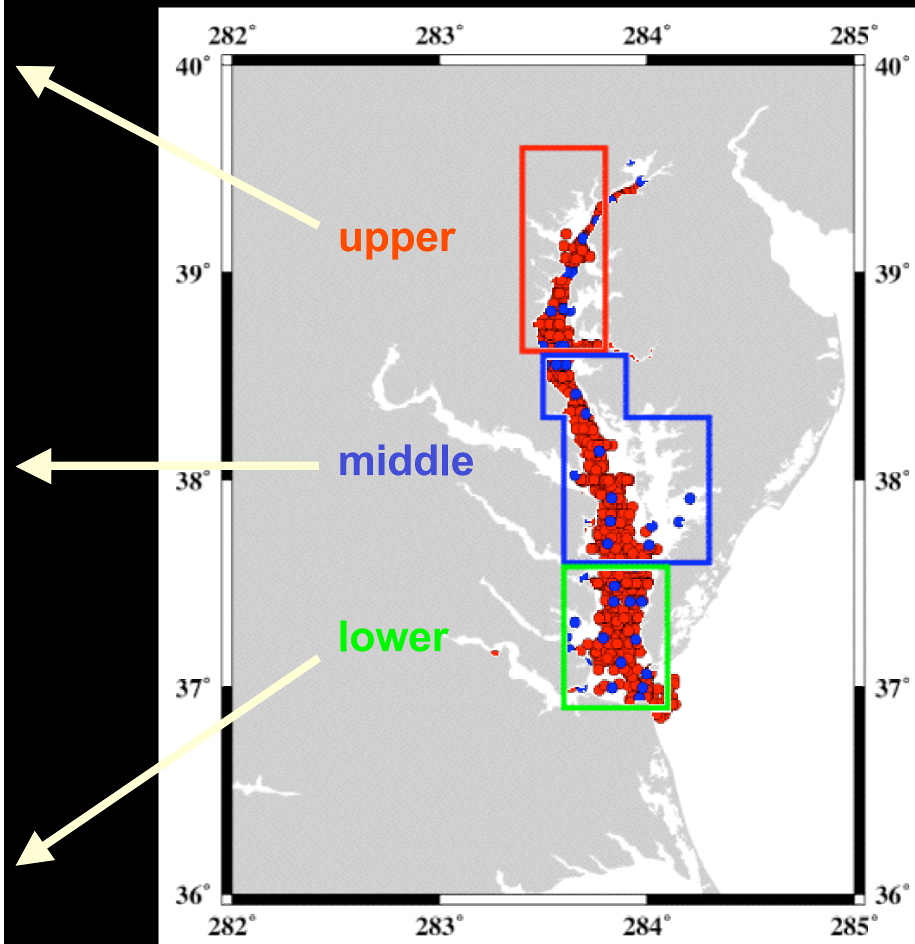
- Model does not work well in high turbidity
- Alternative for turbid water aerosol corrections: **SWIR bands**
  - $L_w \sim 0$ even in most turbid waters due to extremely high water absorption
  - SeaWiFS: no SWIR bands
  - MODIS: 1240, 1640, 2130 nm bands
    - Aqua: 1640 band inoperative (bad detectors)
    - Low SNRs
  - VIIRS 1240, 1610 nm bands
    - SNRs only slightly higher than MODIS



NIR SWIR

Satellite vs In Situ





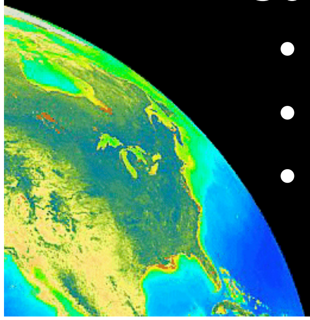
Chesapeake Bay

Atmospheric Correction Issues

- Absorbing aerosols
  - Concentrations below cloud mask reflectance threshold
  - No methodology for even flagging low concentrations
- NIR calibration
  - No reliable methodology for vicarious adjustment of 865 nm, 869 nm and MODIS SWIR bands
- Turbid water aerosol corrections
- NO_2 temporal & spatial coverage
  - For SeaWiFS, requires GOME, Sciamachy, and OMI cross-calibrated data.
  - Requires significant spatial interpolation to fill gaps

Future Directions

- Current sensors (SeaWiFS, MODIS, etc.)
  - Update aerosol models
    - New model suite being tested
    - Model properties consistent with coastal/island AERONET data
  - Evaluate utilization of Calipso & Glory data in SeaWiFS & MODIS atmospheric corrections, especially for absorbing aerosols
- ACE
  - Absorbing aerosol identification & atmospheric corrections
    - Combination of lidar and polarimeter aerosol height & type inputs
  - UV band aerosol corrections
  - Use of UV bands for coastal/turbid water aerosol corrections
    - Assumes insignificant reflectance
  - Coupled ocean-atmosphere RT-based aerosol corrections
    - Several models published to date.
    - Computationally too demanding for routine global processing at this time
    - Performance improvement not dramatic except in presence of absorbing aerosols

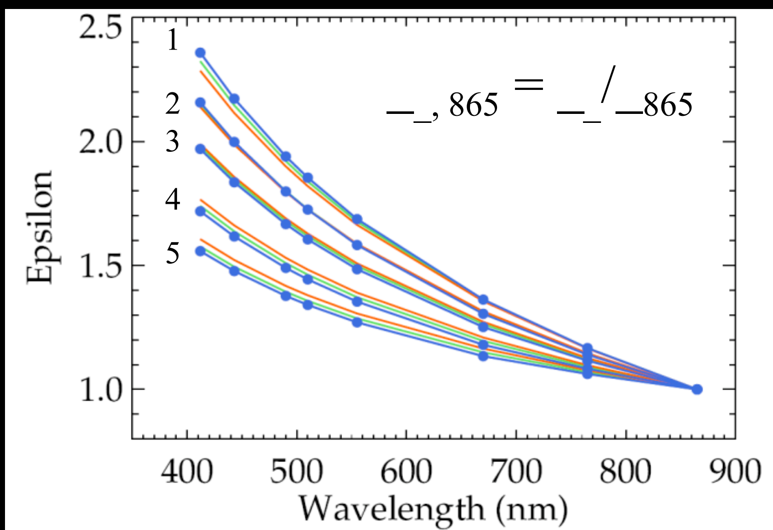


Atmospheric Correction Methodology

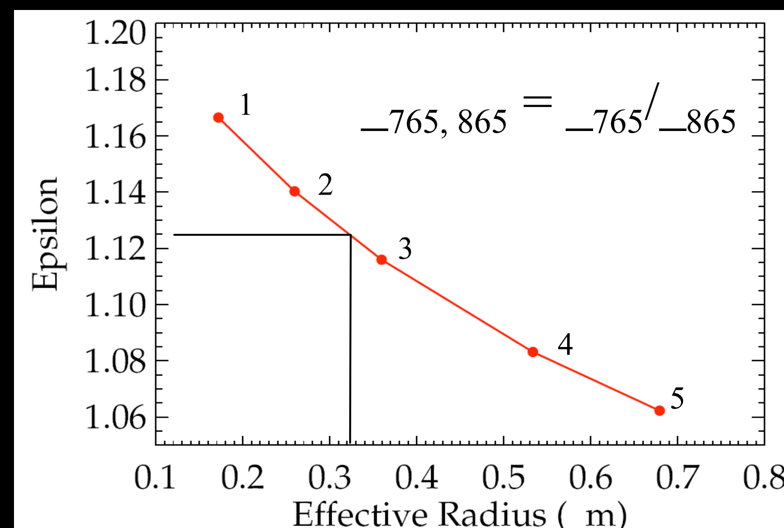
- Aerosol Model Selection
  - OC processing uses NIR measurements to select aerosol model

$$\_765, 865 = \_765/\_865$$

$\_{WL}$ (_)=0



$\_{WL}$ (_)=0

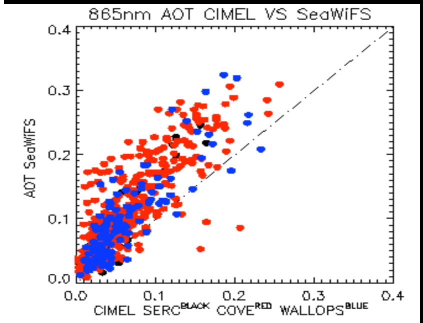


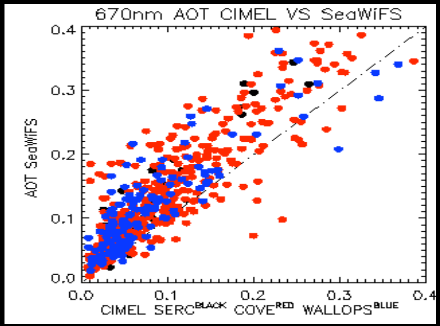
- Select two models that bracket the observed $\_{765, 865}$
- In operational processing we use ratio of single-scattering-reflectance values to compute $\_{765, 865}$

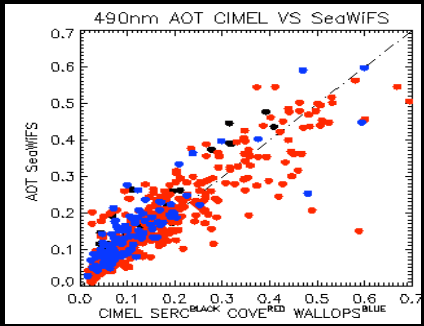
Aerosol Opt. Thickness (MODIS vs. AERONET)

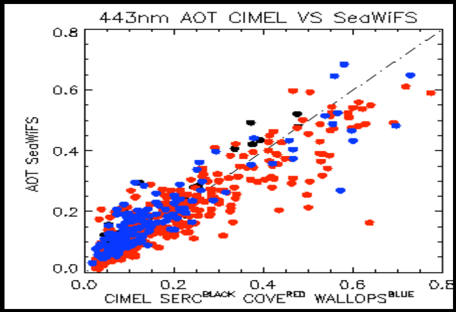
Comparisons from 3 AERONET sites around Chesapeake Bay

AOT Based on Operational Models

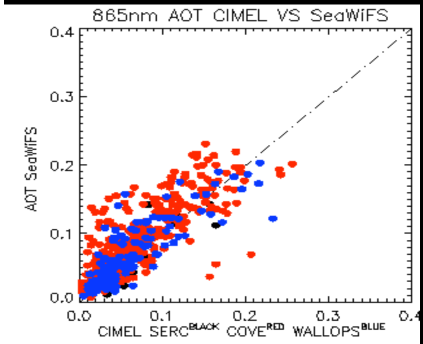


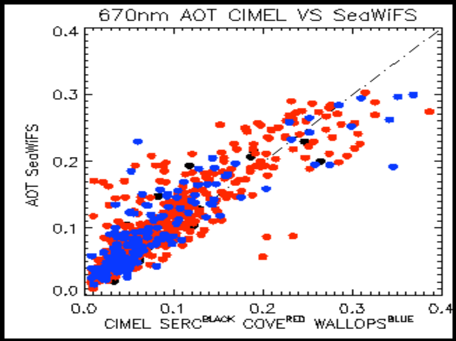


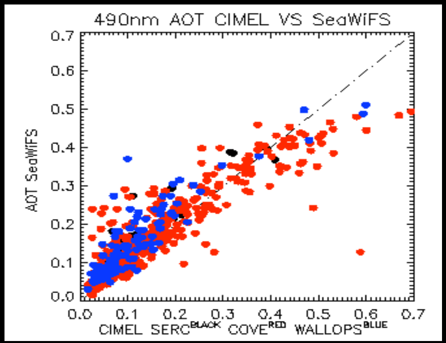


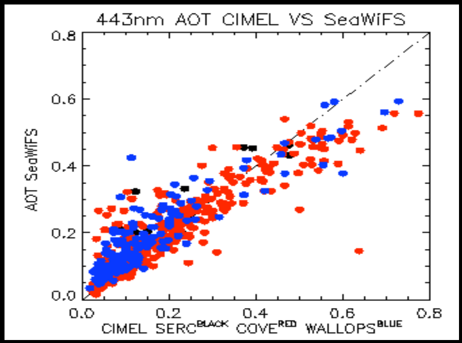


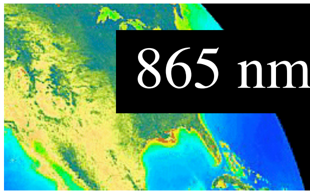
AOT Based on New Models







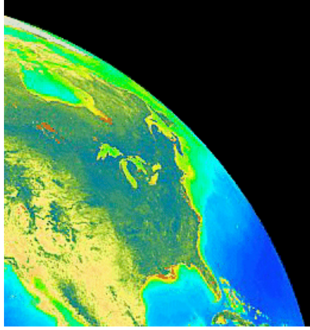




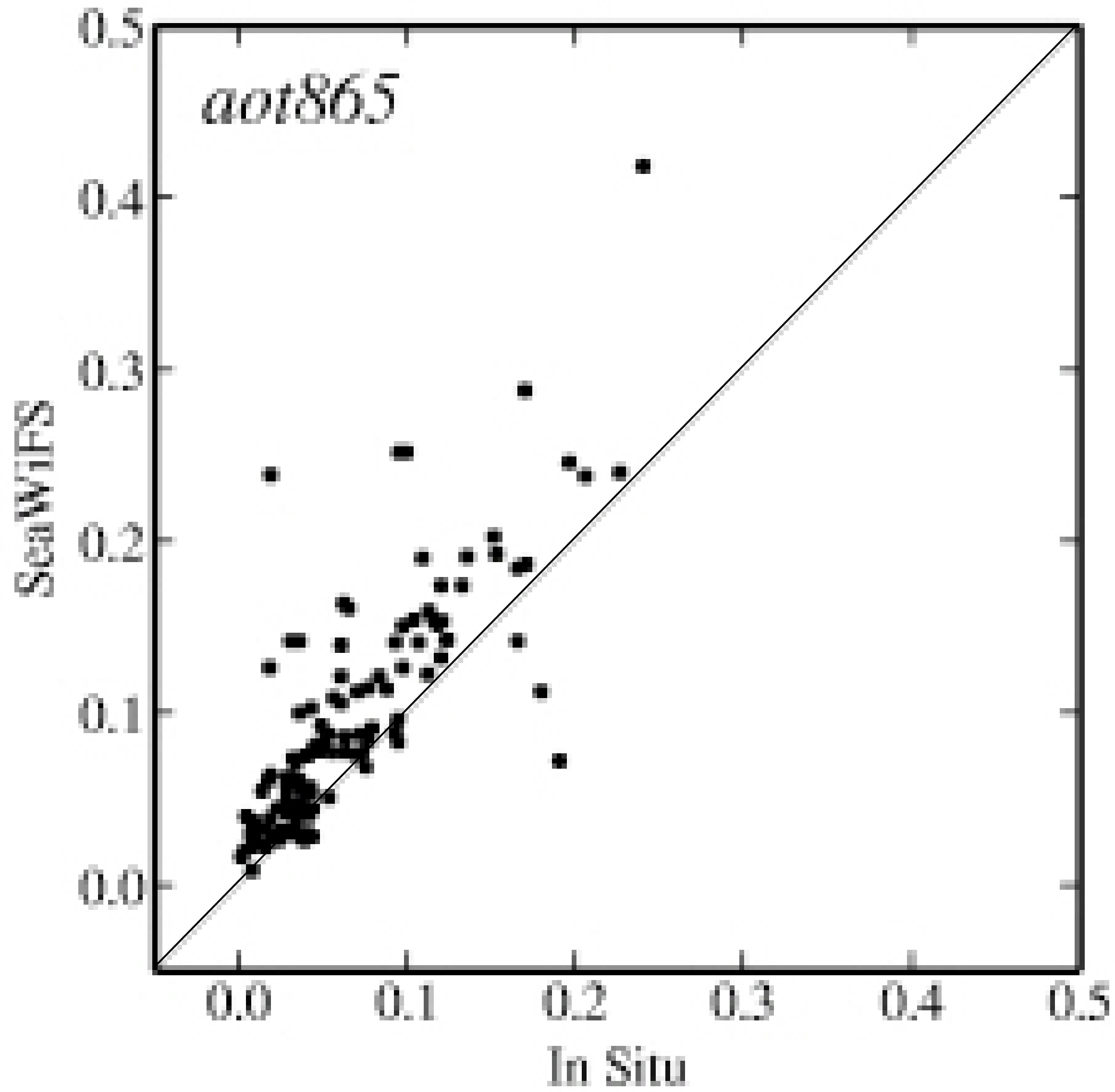
865 nm 670 nm 490 nm 443 nm

AOT range: 0 – 0.7

BACKUP SLIDES



Aerosol Optical Thickness Retrievals



Similar bias found in MODIS/Aqua retrievals.